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A NUMERICAL SCHEME FOR PREDICTING TRANSIENT SHOCK, BOUNDARY LAYER, AND MAGNETOHYDRODYNAMIC PHENOMENA

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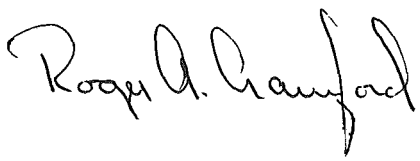
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A stable procedure of first order accuracy for solving the coupled axisymmetric transient gasdynamic and electromagnetic equations is presented. A numerical integration technique developed by Matuska for inviscid flow is extended to include viscous and electromagnetic terms with stability, convergence and computational speed comparing favorably with other existing hydrocodes. In this investigation, the method is applied to a number of transient hydrodynamic and magnetohydrodynamic applications characterized by

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20. ABSTRACT (Continued)

by the interaction of gasdynamic, electromagnetic and viscous flow phenomena.

The external flow field around an M-117 warhead, an ablating reentry vehicle and a semi-infinite circular cylinder, and the internal flow of a nozzle, shock tube and MHD channel is examined under viscous and inviscid conditions. Attention is focused on the behavior of a conducting fluid in the presence of shocks, boundary layers, heat transfer and electromagnetic fields. Finally, the investigation of an MHD generator is described with emphasis placed on aerodynamic and viscous effects influencing the behavior of the energy conversion process. Results of these calculations are shown to be in close agreement with experiment and other theoretical solutions.

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PREFACE

The work reported herein was conducted by the author during periods of Air Reserve active duty at the Arnold Engineering Development Center, Air Force Systems Command under Program Element 65807F and while a graduate student at Auburn University, Auburn, Alabama. The effort was also supported in part by the University of Tennessee Space Institute, Tullahoma, Tennessee and by the Armament Development and Test Center, Eglin AFB, Florida under Project No. 9991VX13.

AEDC Project Managers were Lt Col J. R. Roland and Lt Col R. A. Crawford; Capt K. L. Kushman served as technical advisor.

With the exception of Appendix C, this report was presented as a dissertation in partial fulfillment of the requirements for a Doctor of Philosophy degree at Auburn University in June 1978 and was published as a thesis. That thesis was copyrighted by the author, Capt Laurence A. Feldman. The copyright holder has granted the Government a royalty-free unlimited license to use, duplicate, or disclose copyrighted material in whole or in part and to permit others to do so.

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I. INTRODUCTION

Finite integration techniques are commonly employed to numerically solve mathematical models of physical problems, when the essential features of the model preclude exact analytic solutions. Nayfeh (1) points out that these features include nonlinearities, variable coefficients, complex boundary shapes and nonlinear boundary conditions at known or, in some cases, unknown boundaries. In the case of magnetohydrodynamics or gasdynamics, all of the above undesirable features exist and must be treated.

The primary objective of this dissertation is to solve the viscous gasdynamic and electromagnetic equations of motion in their most fundamental form. The numerical approach selected is finite differencing. Naturally, a numerical solution to these complex and highly nonlinear coupled partial differential equations will place the greatest burden on the computer; however, when considering the futility of employing other non-discretized approaches to meeting the same objective the demands placed on the computer become less significant.

1.1 Motivation

The need for investigating the behavior of a conducting fluid, both experimentally and theoretically, has been well established over the past few decades. However, a review of the literature relevant

to magnetohydrodynamic technology (Section 1.2) reveals that the progress by computational magnetohydrodynamicists has been somewhat limited.

The major obstacles to the development of a numerical approach for solving the equations which govern MHD flow were:

(1) small and slow computers unable to accommodate the demands of most numerical integration techniques; and

(2) a lack of accurate and converging finite difference schemes describing the equations governing MHD phenomena.

The primary objective of this dissertation is to develop a numerical procedure for investigating the complex and highly nonlinear hydrodynamic, viscous and electromagnetic behavior of a conducting fluid. Emphasis was placed on the transient coupling between the gasdynamic and electromagnetic fields. A two-dimensional finite difference technique was developed to model the transient behavior of this fluid.

Traditional methods for solving inviscid or viscous problems such as the method of characteristics (hyperbolic system) or similarity solution and asymptotic expansions suffer from a lack of generality and are restricted by limiting assumptions, neglected terms and inexact linearization of the original governing equations. Further, shocks or subsonic/supersonic regions have to be treated separately and create problems associated with matching solutions derived by different methods as well as cumbersome bookkeeping in satisfying the Rankine-Hugoniot relations across the shock. If the viscous and inviscid calculations are performed separately, a priori information is required as the exact location of the boundary separating the two regions and may lead to inconsistencies if improperly matched.

A discretization approach to the equations of motion in the form of finite difference expressions has significant advantages over the previously mentioned techniques. Namely, this method is consistent throughout all flight regimes, subsonic through hypersonic, and treats the viscous and inviscid regions in identical fashion. The time-dependent problem is considered where some initial set of conditions are imposed and the steady-state solution is generated as the limiting case. Shocks or discontinuities* develop naturally from imposed boundary conditions and the Rankine-Hugoniot equations are automatically satisfied as would be expected since they are expressions of the conservation equations approximated by finite difference terms. Nonlinear terms present no additional complexity if treated explicitly (Section 1.3) even when property values are a function of state values. The interaction of gas dynamic and electromagnetic fields is numerically treated simultaneously and eliminates the need for solving each independently and then iterating both fields to a compatible and converging solution.

Dealing directly with the equations of motion through the finite difference equations, the hydrodynamicist becomes a spectator** to the influence of the physical laws of nature on the dynamic behavior of fluids as opposed to other techniques where the physical processes are obscured by mathematical abstractions, substitutions and approximations.

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*"Numerical diffusion" is inherent in all discretization methods and tends to spread or smear discontinuities over at least two cells. Although the shock thickness is unrealistic, the jump conditions before and after the shock are quite accurate.

**Employing adequate computer graphics (vector, contour, shading plots; computer movies), the user "observes" the occurrence of the phenomenon without having to resort to cumbersome data reduction and analysis.

The primary disadvantage of hydrocodes* is that the numerical procedure is costly in computer time and in some cases computer storage.

Analytic investigations reduces a physical phenomenon to a set of mathematical equations with appropriate boundary and/or initial conditions. The MHD generator problem is composed of many interacting phenomena, each of which if treated independently would constitute significant mathematical problems in the areas of thermodynamics, heat transfer, boundary layer theory, electromagnetism, aerodynamics, fluid mechanics and energy conversion. The MHD generator problem was chosen because it not only represents one of the more severe challenges to a finite difference technique, but the results of such a program would also benefit the progress made in MHD power technology.

1.2 Previous Calculations

Although the past two decades have seen progress in the development of magnetohydrodynamic technology mostly through experimentation, analytic models developed since 1957 have contributed in varying degrees to present understanding of the interaction between gasdynamic and electromagnetic forces. Initially, attention was focused on MHD accelerators with interest directed toward aerospace or military application. More recently, interest has centered on the use of MHD power generators to increase the efficiency of extracting energy from natural resources.

The performance of an MHD generator in converting thermal/kinetic energy into electrical energy is significantly influenced by thermo-

*A finite difference computer program solving the inviscid equations of motion.

dynamic/hydrodynamic effects of: compressibility, viscosity, shocks, heat transfer, non-scalar conductivity and Hall current in addition to electrode and material performance and such design aspects as size, configuration and geometry. Accurate modeling of a generator must take into account the above phenomenon.

The fundamental difficulty in developing a computational model for predicting magnetohydrodynamic phenomena is the coupling of equations governing both the gas dynamic flow and the electromagnetic (EM) fields. Since the flow fields affect the EM fields and vice-versa, the non-linear partial differential equations must be solved simultaneously and stability and convergence of the solutions become greatly complicated (Figure 1).

Approaches to solving MHD problems have consisted of the following:

(A) One-dimensional "influence coefficients."

(B) One-dimensional closed form analytic solutions to ordinary differential equations.

(C) Similarity transformation and closed form solutions to a modified differential equation in one or two dimensions.

(D) One-, two-, and three-dimensional numerical solution to the uncoupled steady MHD equations.

(E) One-, two-, and three-dimensional numerical solution to the coupled steady MHD equations using either the magnetic induction equation or the elliptic equation governing the electric fields and currents.

(F) One-, two-, and three-dimensional transient numerical solution to the coupled MHD equations using either the magnetic induction equation or the elliptic equation.

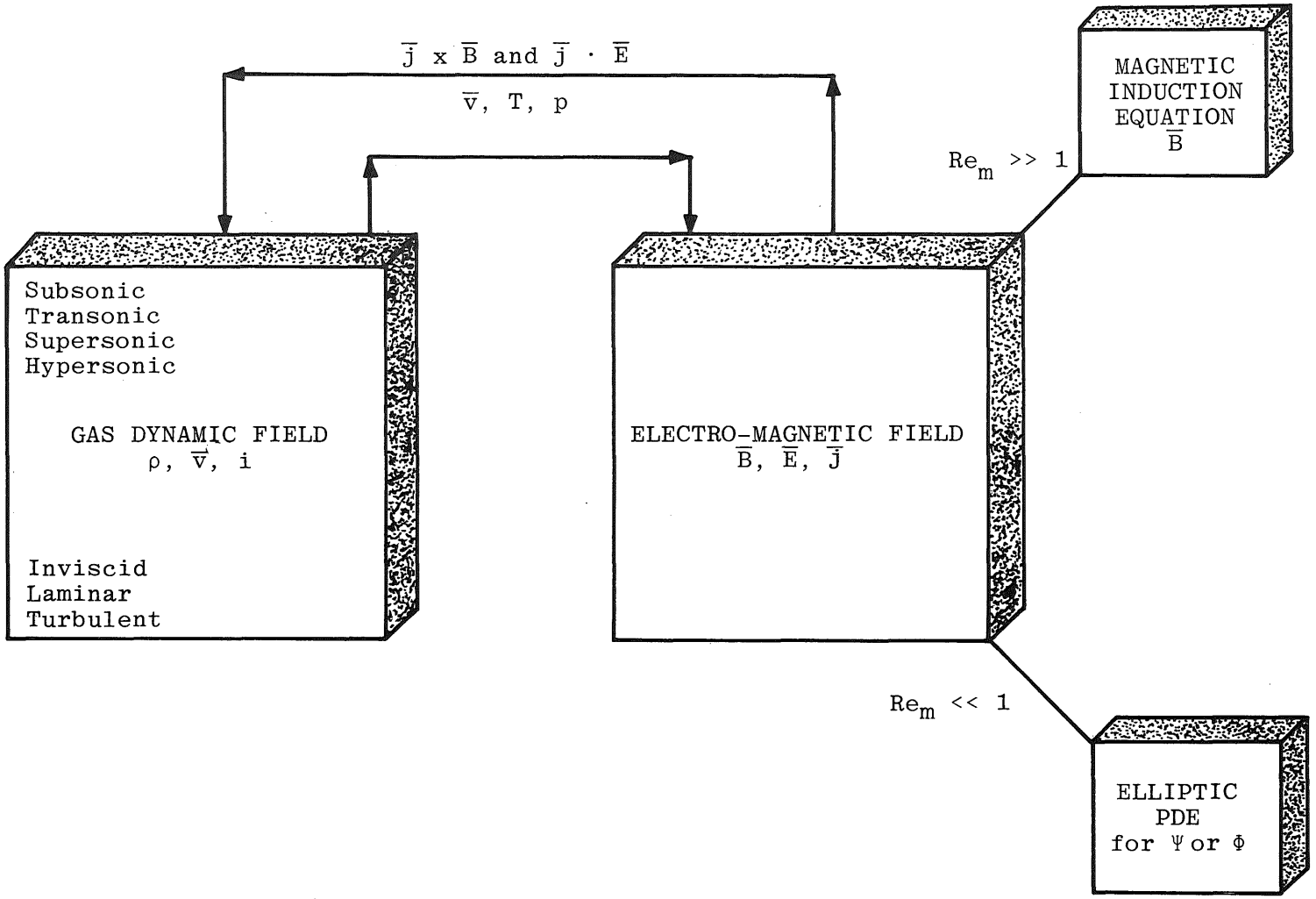


Fig. 1 Flow Diagram of Gas Dynamic-Electromagnetic Coupling

Methods (A), (B) and (C) are exact but are restricted to a narrow range of problems. Approaches (D) and (E) provide rapid convergence to a steady state solution but do not consider the transient behavior between the gas dynamic and electromagnetic fields, or sometimes the strong coupling between the two sets of fields. The last method, (F), is desirable since it treats a wide range of problems, it suffers, however, from large computational times.

A literature survey was performed on the subject of "theoretical modeling of MHD calculations" and is presented in six subsections: (1) hydrocodes; (2) MHD hydrocodes; (3) MHD boundary layers; (4) electric potential and current stream functions; (5) MHD shocks; and (6) simplified MHD analysis.

Hydrocodes

There are at present hundreds of existing hydrodynamic computer programs commonly referred to as "hydrocodes" as discussed in Section 1.3. They are categorized as either Eulerian or Lagrangian, explicit or implicit, viscous or inviscid, etc. The origin of these programs can be traced to less than a half dozen sources and although each hydrocode has been tailored by its own evolutionary process, the fundamental nature of all codes can be categorized into a small class of finite difference techniques. This is not to imply that the stability or convergence or rate of convergence of these programs are equivalent; some programs remain stable and give accurate solutions for a limited

number of problems over a restricted integration region, whereas other methods can treat a wider variety of problems under more severe numerical conditions.

Pioneers in the field of hydrocodes can be traced to those organizations equipped with the most advanced computer systems. Some leading theoreticians (2-4) began work in the late 1940's which resulted in the development of hydrocodes beginning in the early 1950's (5-17). Numerous authors (18-20) have made comparisons of these finite difference techniques.

MHD Hydrocodes

A number of MHD hydrocodes exist with the predominant number employing implicit schemes and solving the magnetic induction equation instead of the elliptic equation describing the stream function or potential. Roberts and Potter(21) and Killeen (22) discuss finite difference equations and MHD hydrocode applications. In 1963, Roberts, et al., (23) developed "THETATRON," employing the magnetic induction equation, designed to treat plasma problems such as "theta pinch containment." Freeman and Lane (24) developed in 1969 an explicit, Eulerian, Lax-Wendroff MHD technique. Two-dimensional laminar compressible MHD flow problems were treated by Fritzer, et al., (25) in 1972. Eddy currents were calculated using a modified FLIC (Fluid In Cell), PLIC (Plasma In Cell) and employing the donor-receiver technique (see Appendix A.1). It was found that since the ratio of the speed of light to sound was many orders of magnitude, the induction equation had to be solved at this same ratio for each gas dynamic time iteration. It was determined that gradients of velocity, conductivity

and magnetic field can tailor the shape of stream currents in a desired fashion.

Other techniques were developed (26-29) for plasmas which solve the magnetic induction equation. Fajen (26) in 1973 used the Harlow and Amsden "ICE" code and modified it to a Lax-Wendroff scheme. Brackbill and Pracht (27) in 1973 extended the "ICE-ALE" technique into an "almost-Lagrangian" (11) implicit scheme. Gubarev (30) in 1973 employed the assumption of small magnetic Reynolds number and investigated the stagnation of supersonic flow of a conducting gas in an MHD channel with Hall currents. One electrode was considered. In 1974 Ostretsov (31) divided the system into two subsystems, one containing the equations describing the EM fields and the other describing the gas dynamics, and constructed an iteration scheme between the two. Lindemuth (29) in 1974 employed an alternating direction implicit scheme to treat plasmas of high magnetic Reynolds numbers. Bakhrakh and Gubkov (32) used a 2-D axisymmetric finite difference method with finite conductivity and an azimuthal magnetic field. The solution was developed in three phases: (1) computing the hydrodynamics, while freezing the magnetic flux, (2) while freezing the fluid dynamic state, computing the induced magnetic field, and (3) computing Joule heating. It was determined that the order in which these three phases were carried out did not affect the final results.

MHD Boundary Layers

In the late 1950's, Rossow and Bush (33-35) studied the interaction of a conducting, viscous fluid with an applied magnetic field. It was found that the drag, skin friction and heat transfer were affected by

the strength of the magnetic field which in turn could be exploited to control the motion of a fluid. Sherman (36) in 1961 studied the influence of a nonuniform magnetic field on a Blasius boundary layer. Others including Sears, Hunter, Wu, Taylor, Denzel, High and Felderman (37-40) studied the effects of nonuniform properties of an equilibrium plasma in a segmented MHD generator assuming laminar or turbulent velocity profiles. Dix and Dukowicz (41,42) considered a solution to the equations of motion for flow over a flat plate boundary layer under the influence of a transverse magnetic field for low magnetic Reynolds number. Monis, Eustis, Krueger and Self (43) in 1973 matched a 1-D gas dynamic solution with a 1-D boundary layer solution under the influence of a magnetic field. Doss, Dwyer and Hoffman (44) investigated compressible laminar and turbulent boundary layers in an MHD channel. Also in 1973, Derkach and Zhigula (45) developed a closed form analytic solution to flow over a long cylinder under a radial magnetic field. The work of Demetriades, Argyropoulos and Maxwell (46) consider two- and three-dimensional solutions to viscous flow in MHD generators and accelerators.

Electric Potential and Current Stream Functions

The 2-D Laplace equation of the electric potential or the current stream function, discussed in Section (2), was solved initially by conformal mapping (47-51). End effects, variable geometry and concentration of current resulting from Hall current around electrodes were investigated. Dzung (52) in 1962 employed a series solution, whereas Sherman (53) considered conductivity a function of current and developed a solution using an expansion technique. More recently,

Poberenzhskii and Yakkot (54) employed an analytic solution using the method of images of vortex source combinations. Crown (55) was the first to attempt a numerical relaxation technique but developed numerical instabilities for Hall parameters greater than 2. Celinski and Fischer (56) in 1966 eliminated this numerical problem by modifying the numerical technique and calculated solutions with Hall parameters up to 10. Louis, Lothrop and Brogan (57) used simple theories for flow with uniform properties and predicted fluctuations of current distribution in time and space, particularly near electrodes. Finally, Oliver (58) considered instabilities due to spatial nonuniformities in the electrical conductivity from inhomogeneous mixing of ionizable species, resulting from variable fluid properties or nonuniform Joulean heating. Relaxation techniques were employed to investigate these instabilities.

MHD Shocks

There are numerous papers concerning MHD shocks and Alfven waves. Some analytic expressions for MHD shocks were developed by Greifinger and Cole (59) and Natter (60). Numerical calculations were performed by Chu and Taussig (61), Sutton and Sherman (62), and Shank and Morse (63), the latter two employing the "Particle In Cell" method developed by Harlow, et al. The use of magnetic fields to displace shocks on re-entry vehicles was discussed by Resler and Sears (64) and Ziemer (65) in their papers concerning the prospects of "magnetoaerodynamics."

Simplified MHD Analysis

Other MHD analysis included the work of Sutton (66) in 1959 who discussed the relationships which govern the performance of constant

velocity, temperature, pressure, density and area generators, whereas Swift-Hook (67) considered a constant temperature generator. MHD flow parameters were studied by Wilson, et al., (68) by employing 1-D influence coefficients which governed the behavior of the fluid under pressure, temperature, friction area change and Lorentz force terms. Similarly, Zampaglione (69) considered choking in a constant area channel and Chubb (70) studied an MHD nozzle.

One-dimensional analysis of MHD flow was investigated by Neuringer (71) using the method of calculus of variation in seeking conditions for optimum power generation. Brocher (72) and Blecher (73) studied in 1961 a constant velocity MHD generator with variable conductivity and developed closed form expressions yielding generator performance. Ralph and Harwell (74) in their discussion of power and performance of MHD generators determined that since power is proportional to conductivity times velocity squared, an optimum ratio of internal to kinetic energy will yield an optimum Mach number resulting in optimum power.

Other studies include the work of Sonnerup (75), Roy and Wu (76) and Sherman and Sutton (77), who considered incompressible constant property 2-D flow under the influence of a tensor conductivity and segmented electrodes.

The performance of MHD generators was also investigated by others (78-87); those investigators considered the adverse influence of boundary layers (laminar and turbulent), Hall current, separation, end effects, external loading and geometry on the power and efficiency of generators.

1.3 Fundamentals of Numerical Methods

This dissertation illustrates the stability and, where practical, the convergence and compatability of a numerical technique to be subsequently described through application to a number of problems outlined in Section 1.4.*

A method is called stable if any bounded starting procedure yields a uniformly bounded solution of the difference equation as the step size goes to zero. A method is converging if the values of the solution to the finite difference equations (FDEs) approximating the differential equation tend to the values of the exact solution to the differential equation. Finally a method is compatible if the truncation error goes to zero as the step size goes to zero (88). Thus, if a method is stable, converging and compatible, the solution to the finite difference equations is bounded, its error is influenced by the step size and the differential equation solved by the FDEs is indeed the differential equation under investigation.

If a finite difference technique is used to approximate a set of equations, it is characterized by the time and space coordinate systems employed. A coordinate system fixed to the moving fluid (constant mass) is known as "Lagrangian," whereas a coordinate system fixed in space (constant volume) is categorized as "Eulerian." If the time derivative of variable f is evaluated based on values of f at other locations, also being simultaneously evaluated, the method is

---

*A rigorous mathematical stability analysis was not performed.

referred to as "implicit," whereas if the time derivative of variable f is evaluated based on values of f at other locations and these values are already known from a previous time, the method is identified as "explicit." The basic advantages and disadvantages of the Lagrangian, Eulerian, implicit and explicit methods are outlined below. The convenience in treating boundary conditions and grid distortion play major roles in the selection of the method employed.

Given a partial differential equation such as:

$$\frac{d}{dt}(u) = L(u) \qquad (1)$$

where L is a differential operator with independent space coordinates, the integration of u may be performed by two methods: explicit or implicit

where

$$\int \frac{d}{dt}(u)\,dt = \int L(u)\,dt \qquad (2)$$

$$u_{i,j}^{n+1} - u_{i,j}^{n} = \varepsilon \Delta t L^{n+1}(u_{i,j}^{n+1}) + (1-\varepsilon)\Delta t L^{n}(u_{i,j}^{n}) \qquad (3)$$

$$\Delta t = t^{n+1} - t^{n} \qquad (4)$$

and ε = integration parameter; explicit = (0), implicit = (1). If $\varepsilon = 0$,

$$u_{i,j}^{n+1} = u_{i,j}^{n} + \Delta t L^{n}(u_{i,j}^{n}) \qquad (5)$$

The explicit calculation provides values for u at time (n+1) based on values of u at time (n), which are obviously all known. However, numerical stability for an explicit technique restricts the time step, and thus the rate of convergence to a steady state solution.

A discussion of the stability criteria follows, but its physical interpretation suggests that, "The rate of propagation of information by the finite difference solution across a mesh cannot exceed one space-step during each time-step and must be able to keep up with all propagation speeds of the differential system, including waves, fluid motion and diffusion." (21) The most unfavorable local case (smallest cell, largest signal velocity) must necessarily be taken.

If $\varepsilon = 1$,

$$u_{i,j}^{n+1} = u_{i,j}^{n} + \Delta t L^{n+1}(u_{i,j}^{n+1}) \qquad (6)$$

and the implicit integration computes u at time (n+1) based on neighboring values of u also at time (n+1) which are not known. If the L operator is linear, then the solution to the equations has been reduced to the solution of a set of simultaneous algebraic equations at each time step. The matrix is tri-diagonal and can expeditiously be inverted algebraically (3).

In the former explicit case, all terms on the rhs are known, and each updated value of u is individually computed. In the latter implicit case, values on the rhs of the FDE are not known and values for the neighboring points must be computed simultaneously by either matrix inversion, if the equations are linear, or some iteration procedure, if the equations are nonlinear.

Although the time interval of an implicit calculation is not restricted by the speed at which signals propagate (primarily the local speed of sound), it is regulated by the particle velocity and cell size. Since the computation time for an implicit time step calculation is four

to five times greater than that for the explicit calculation, problems where the flow field has speeds in excess of Mach 0.2 to 0.25 will be more efficiently computed explicitly. Also, representing the FDEs in the form of simultaneous algebraic equations which may be cast in the traditional tri-diagonal matrix, nonlinear terms must be either ignored or treated explicitly. Thus implicit programs work most efficiently for incompressible linear problems and compare unfavorably at high subsonic speeds.

Many existing hydrocodes claim to be able to solve the transient "initial value problem" (IVP) when in actuality their methods are efficient only for the steady state "boundary value problem" (BVP). In solving the BVP, a unique solution exists for a prescribed set of boundary conditions, providing that these boundary conditions are not time-dependent. The steady state solution is developed by relaxing to the final state from some arbitrary set of initial conditions. Relaxation does not connote solving the transient equations as may be incorrectly assumed. Implicit programs converge to the steady state solution more rapidly than explicit programs because of the more stringent stability criteria plaguing the explicit method. However, for the IVP, where transient behavior is considered, implicit programs are not competitive because either large time steps as employed in the BVP will result in a grossly inaccurate transient solution or smaller time steps yields a more expensive calculation when compared with the explicit approach. In a complex problem, where such phenomena as shocks reflecting or interacting with boundary layers occur over a period of microseconds, one cannot expect much fruition from a calculation which "smears" this

behavior over a time step of milliseconds. It is therefore emphasized that "pseudo-transient" implicit techniques which do not violate any stability criteria do not necessarily converge.

In the explicit scheme, since the new value of the dependent variable is based on the old value of its neighbors, a large step size, or one that exceeds a stability bound, can obviously lead to an instability because the change may be unrestrained. In the implicit scheme, however, since the new value of the dependent variable is based on the new value of its neighbors, all values of the dependent variable (including boundary values) are implicitly "tied" to each other and serve as a restoring or restraining force on the behavior of the dependent variable in ensuing iterations. Although the implicit scheme is stable usually under the severest of conditions (large step size, high nonlinearity, etc.) the accuracy of its solutions will suffer significantly if controls are not placed on the step size.

A basic problem in solving the equations governing MHD flow is the simultaneous treatment of numerous physical processes: magnetic, thermal, viscous transport, hydrostatic compression, etc. Starting with known initial conditions in density, velocity, energy and magnetic induction (or electric potential or stream current), the transient response of a fluid under prescribed boundary conditions is computed at selected time intervals. These intervals, although desired large in order to minimize computational time, are unfortunately for an explicit scheme strongly dictated by some basic stability criteria which implicitly expresses the speed of a signal of some wave or diffusive phenomenon. Lagrangian integration (fixed mass) is significantly influenced by

advective terms in the governing equations. "The transport of physical variables such as density, temperature, magnetic field and velocity from point to point by the bulk motion of the fluid is represented by $\bar{v}.\nabla$ terms. Superimposed on these terms are other kinematic effects such as adiabatic compression or diffusion. Clearly a Lagrangian formulation using a mesh which moves with the fluid can transform away the bulk motion altogether allowing the remaining terms to be treated more accurately." (3) If however, the convective terms dominate, then the grid frozen to the mass becomes severely distorted and results in large discretization error. Rezoning the mesh, periodically, can result in large conservation errors. "A fixed Eulerian mesh is normally used in practice and thus requires careful treatment of the advective (convective) term if physical diffusion is not to be masked by numerical effects." (Ref. 3)

The time step over which each integration (cycle) is performed is governed by stability criteria.

Stability conditions which control the time step Δt are:

(A) The Courant condition:

$$\frac{\Delta z}{\Delta t} > c \; ; \; \frac{\Delta r}{\Delta t} > c \qquad (7)$$

(B) The particle velocity condition:

$$\frac{\Delta z}{\Delta t} > u \; ; \; \frac{\Delta r}{\Delta t} > v \qquad (8)$$

which prohibits the transmission of a signal or mass across more than one cell in one time interval.

(C) Viscosity condition:

$$\frac{2}{3}\frac{\mu}{\rho(\Delta z)^2} < \frac{1}{\Delta t} \; ; \; \frac{2}{3}\frac{\mu}{\rho(\Delta r)^2} < \frac{1}{\Delta t} \tag{9}$$

$$\frac{\mu_E}{\rho(\Delta z)^2} < \frac{1}{\Delta t} \; ; \; \frac{\mu_E}{\rho(\Delta r)^2} < \frac{1}{\Delta t} \tag{10}$$

(D) Alfven condition:

$$\frac{1}{\Delta r}\frac{B^2}{\mu_p \rho} < \frac{1}{\Delta t} \; ; \; \frac{1}{\Delta z}\frac{B^2}{\mu_p \rho} < \frac{1}{\Delta t} \tag{11}$$

Employed in conjunction with the solution of the magnetic induction equation which prohibits the transmission of an Alfven wave across more than one cell in one time interval.

(E) Thermal conductivity condition:

$$\frac{\lambda}{\rho c_p(\Delta z)^2} < \frac{1}{\Delta t} \; ; \; \frac{\lambda}{\rho c_p(\Delta r)^2} < \frac{1}{\Delta t} \; : \text{laminar} \tag{12}$$

$$\frac{\lambda_t}{\rho c_p(\Delta t)^2} < \frac{1}{\Delta t} \; ; \; \frac{\lambda_t}{\rho c_p(\Delta r)^2} < \frac{1}{\Delta t} \; : \text{turbulent} \tag{13}$$

(F) Magnetic diffusion condition:

$$\frac{1}{\sigma \mu_p(\Delta z)^2} < \frac{1}{\Delta t} \; ; \; \frac{1}{\sigma \mu_p(\Delta r)^2} < \frac{1}{\Delta t} \tag{14}$$

(G) Lorentz condition:

$$\frac{\sigma B^2}{\rho} < \frac{1}{\Delta t} \tag{15}$$

Considering all phenomena, the time step becomes:

$$\Delta t = \Delta z/\{u+c+ \frac{2}{3}\frac{\mu}{\rho\Delta z} + \frac{\mu_e}{\rho\Delta z} + \frac{B^2}{\rho\mu_p}\Delta z + \frac{\lambda+\lambda_T}{\rho c_p \Delta z} + \frac{1}{\sigma\mu_p\Delta z} + \frac{\sigma B^2}{\rho}\Delta z \} \quad (16)$$

$$\Delta t = \Delta r/\{v+c+ \frac{2}{3}\frac{\mu}{\rho\Delta r} + \frac{\mu_e}{\rho\Delta r} + \frac{B^2}{\rho\mu_p}\Delta r + \frac{\lambda+\lambda_T}{\rho c_p \Delta r} + \frac{1}{\sigma\mu_p\Delta r} + \frac{\sigma B^2}{\rho}\Delta r \} \quad (17)$$

where Δt is evaluated at each cell and the minimum value employed.

1.4 Scope of Present Work

The objective of this investigation is to demonstrate a numerical procedure which can predict the transient aerodynamic behavior of a (conducting) fluid under the influence of viscous and/or electromagnetic forces. Calculations are performed in two-dimensions (axisymmetric), although the technique can be easily expanded to treat three-dimensional flow. Further, although variations in the grid formation or integration technique may be employed to improve the program's computational efficiency, these efforts were considered beyond the scope of this study.

The programs flexibility to treat physical phenomena is demonstrated through solution to classical problems which consider:

I. Compressibility:

   A. Incompressible (Blasius problem)

B. Compressible (nozzle flow)

II. Mach Regimes:

A. Subsonic (M117 Warhead)

B. Transonic (M117 Warhead)

C. Supersonic (sharp-nosed projectile)

D. Hypersonic (re-entry vehicle)

III. Boundary Layers:

A. Laminar (Couette flow)

B. Turbulent (free jet)

IV. Magnetic Reynolds Number regime:

A. High magnetic Reynolds number (MHD shock detachment)

B. Low magnetic Reynolds number (MHD generator)

1. Current stream function

2. Electric potential

V. Heat transfer

A. Thermal conduction (transient temperature diffusion)

B. Viscous dissipation (boundary layer problem)

C. Joule heating (MHD generator)

D. Aerodynamic heating (ablated RV)

VI. Shocks

A. Normal shock (shock tube)

B. Oblique shock (sharp-nosed projectile)

C. Mach stem (regular-irregular Mach reflection)

D. Imbedded shock (ablated RV)

VII. Time dependency

A. Transient (see problems above)

B. Steady state (see problems above)

The program employs three finite difference techniques to integrate time dependent variables:

(A) gas dynamic integration is achieved using the Explicit Method developed by Matuska.

(B) the solution of the elliptic equation (low Re_m) for the electric potential or stream current function employs the method of Successive Over-Relaxation (SOR).

(C) the magnetic induction equation (high Re_m) and the Fourier thermal diffusion term in the energy equation are solved by either a central difference explicit scheme or an Alternating Direction Implicit (ADI) procedure.

An alternating direction implicit technique had been applied to the hydrodynamic equations, but its primary advantage of rapid convergence to steady state solution for some problems was overshadowed by its limitations (Section (1.3)) in treating transient cases and thus precluded its use in solving the conservation equations.

The overriding objective in developing this technique is to treat all interacting phenomena described by their governing equations simultaneously through a set of flexible, self-contained, autonomous finite difference equations where the only input consists of initial and boundary conditions and material constitutive relations.

The added difficulties in solving an MHD problem occur because of the "coupling" effect of the gas dynamic and electromagnetic fields which are interdependent. The MHD generator problem serves as a critical

Challenge for attaining this goal, and represents a clear test in establishing the program's capability to treat other equally difficult applications.

The difference method developed by Matuska and employed by the 2-D HULL Code is fully first order accurate. The HULL finite difference expressions approximate the conservation equations governing a compressible, non-conducting, inviscid fluid. This method was extended to include a two-dimensional single viscous fluid model with six fundamental equations governing the behavior of a conducting fluid: (1) continuity, (2) axial momentum, (3) radial momentum, (4) energy, and from Maxwell's equations and Ohm's Law, (5) magnetic induction or (6) the electric potential or current stream function.

CONSERVATION OF MASS:

$$\frac{d}{dt}(\rho)+\rho(\nabla\cdot\vec{v}) = 0 \qquad (18)$$

CONSERVATION OF MOMENTUM:

$$\rho\frac{d}{dt}(\vec{v})+\nabla p = -\rho\vec{g}-\nabla\cdot\bar{\bar{\tau}}+\vec{j}\times\vec{B} \qquad (19)$$

CONSERVATION OF ENERGY:

$$\rho\frac{d}{dt}(e)+\nabla\cdot(\underline{p}\vec{v}) = -\rho\vec{v}\cdot g-\nabla\cdot(\bar{\bar{\tau}}\cdot\vec{v})-\nabla\cdot\bar{q} \qquad (20)$$

MAXWELL'S RELATIONS:

$$\nabla\times\vec{E} = -\frac{\delta}{\delta t}(\vec{B}) \qquad (21)$$

$$\nabla\times\vec{B} = \mu_p\vec{j} \qquad (22)$$

EQUATION OF STATE:

$$p = p(\rho, i) \tag{23}$$

CONSTITUTIVE RELATIONS:

(A) STRESS TENSOR:

(1) STOKES' LAW (LAMINAR):

$$\tau_{i,j} = \mu\left[\left(\frac{\partial u_i}{\partial X_j} + \frac{\partial u_j}{\partial X_i}\right) - \frac{2}{3}(\nabla\cdot\bar{v})\delta_{i,j}\right] \tag{24}$$

where $u_1 = u$; $u_2 = v$; $X_1 = z$; $X_2 = r$

(2) TURBULENCE (EDDY MIXING LENGTH):

$$\tau = -(\mu+\mu_E)\frac{\delta}{\delta r}(u) \tag{25}$$

$$\mu_E = \lambda_E^2 \frac{\delta}{\delta r}(u) \tag{26}$$

(B) OHM'S LAW:

$$\vec{j} = \bar{\bar{\sigma}}\cdot(\vec{E}+\vec{v}\times\vec{B}) \tag{27}$$

$$\bar{\bar{\sigma}} = \frac{\sigma}{1+\beta^2}\begin{bmatrix} 1 & -\beta \\ \beta & 1 \end{bmatrix} \tag{28}$$

(C) FOURIER'S HEAT CONDUCTION LAW:

$$\bar{q} = -(\lambda+\lambda_t)\nabla T \tag{29}$$

BOUNDARY CONDITIONS:

(A) SOLID BOUNDARY:

$$\vec{v}\cdot\vec{n} = 0 \tag{30}$$

(B) ELECTRODE:

$$\vec{E}\times\vec{n} = 0 \tag{31}$$

(C) INSULATOR:

$$\vec{j}\cdot\vec{n} = 0 \tag{32}$$

(D) electrical relation between the external and internal circuits of an MHD generator.

In order to minimize core requirements and computational cp (central processor) time of an already demanding computational method, three-dimensional problems were considered impractical. The model, however, can be easily extended to a third dimension when the development of advanced computers can accommodate the requirements of hydrocodes, in particular, the excessive cp* time. Turbulence was treated through a simple eddy viscosity model and no attempt was made to use sophisticated viscous theory, as this was also considered to be beyond the scope of this effort.

*cp - Central Processor

II. DISCUSSION OF TWO-DIMENSIONAL PLANE AND AXISYMMETRIC FINITE DIFFERENCE TECHNIQUE.

In Section 1.4, the equations describing the motion of a conducting fluid were presented. This section discusses a numerical procedure which "approximates" these equations by the method of finite differencing. In order to successfully develop a set of finite difference equations to a system of partial differential equations, three conditions must be satisfied: stability, convergence and compatibility. The objective of this study is to establish through a series of physical applications that the equations presented in this section do indeed satisfy these numerical conditions. The non-magnetic partial differential equations to be solved are:

(1) Continuity

(2) Axial momentum

(3) Radial momentum

(4) Energy

with four unknowns: p, u, v and e.

When including MHD effects, one needs in addition for large magnetic Reynolds number:

(5) The magnetic induction equation

with the magnetic induction intensity as the additional unknown.

For problems of low magnetic Reynolds number, one needs

(6) The elliptic partial differential equation governing the

electric potential or stream current function (ϕ or Ψ).

The additional unknown becomes ϕ or Ψ. Pressure, stress, currents and electric fields are computed from the variables discussed above with the additional relations: Equation of State, Ohm's Law and the constitutive relations correlating stress and strain.

2.1 Coordinate Systems

The initial development of a numerical scheme to solve the non-MHD gasdynamic equations treated axisymmetric problems with coordinates r (radial) and z (axial) with aximuthal terms constant ($d/d\theta = 0$). As $r \to \infty$, these equations reduced to a 2-D Cartesian system where the traditional x,y-axis coincide with the z,r coordinates, respectively.

When high Re_m MHD effects were treated, the magnetic induction was considered in the r,z,θ direction without violating the primary assumption of symmetry about the z-axis, since ($d/d\theta = 0$) terms were neglected and $\bar{j}x\bar{B}$ and $\bar{j}\cdot\bar{E}$ contributions occur only in the r-z plane. In the case of low Re_m effects, problems were treated only in Cartesian coordinates and thus the electric potential, stream current function, currents, electric fields and consequently the Lorentz force and electrical energy terms $\bar{j}x\bar{B}$ and $\bar{j}\cdot\bar{E}$ were expressed only in Cartesian coordinates.

In summary, all problems with the exception of the low Re_m MHD applications are solved in either 2-D axisymmetric or 2-D Cartesian coordinates. For low Re_m MHD problems, only 2-D Cartesian coordinates may be employed. In either case, r and z coordinate labels are employed.

2.2 Generalized Equations

The conservation equations are solved in two dimensions in either axisymmetric cylindrical coordinates or Cartesian coordinates as shown in Figure (2).

Equation (33) represents the conservation of mass:

$$\frac{\delta}{\delta t}(\rho)+\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(\rho\cdot v\cdot r^{\alpha})+\frac{\delta}{\delta z}(\rho\cdot u)=0 \qquad (33)$$

where $\alpha = 0$ for rectangular coordinates and $\alpha = 1$ for cylindrical coordinates.

The conservation of axial and radial momentum* are described by

$$\frac{\delta}{\delta t}(u)+v\frac{\delta}{\delta r}(u)+u\frac{\delta}{\delta z}(u)=-\frac{1}{\rho}\frac{\delta}{\delta z}(p)-g_z-\frac{1}{\rho}\left[\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(r^{\alpha}\cdot\tau_{rz})+\frac{\delta}{\delta z}(\tau_{zz})\right]+\frac{1}{\rho}\{[\vec{j}x\vec{B}]_z\} \qquad (34)$$

$$\frac{\delta}{\delta t}(v)+v\frac{\delta}{\delta r}(v)+u\frac{\delta}{\delta z}(v)=-\frac{1}{\rho}\frac{\delta}{\delta r}(p)-g_r-\frac{1}{\rho}\left[\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(r^{\alpha}\cdot\tau_{rr})-\frac{\tau_{\theta\theta}}{r}+\frac{\delta}{\delta z}(\tau_{zz})\right]+\frac{1}{\rho}\{[\vec{j}x\vec{B}]_r\} \qquad (35)$$

The conservation of total energy is expressed as

$$\frac{\delta}{\delta t}(e)+v\frac{\delta}{\delta r}(e)+u\frac{\delta}{\delta z}(e)=+\frac{1}{\rho}\left[\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(p\cdot v\cdot r^{\alpha})+\frac{\delta}{\delta z}(p\cdot u)\right]$$

$$-\frac{1}{\rho}\left[\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(\tau_{rr}\cdot v\cdot r^{\alpha})+\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(\tau_{rz}\cdot r^{\alpha}\cdot u)+\frac{\delta}{\delta z}(v\cdot\tau_{rz})+\frac{\delta}{\delta z}(u\cdot\tau_{zz})\right]+\frac{1}{\rho}\{[\vec{j}\cdot\vec{E}]\}$$

$$-v\cdot g_r-u\cdot g_z-\frac{1}{\rho}\left[\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(-\lambda\cdot r^{\alpha}\cdot\frac{\delta}{\delta r}(T))+\frac{\delta}{\delta z}(-\lambda\cdot\frac{\delta}{\delta z}(T))\right] \qquad (36)$$

---

*Momentum is not conserved because of viscous dissipation and Joule heating. The expression "conservation of momentum" applies to the momentum balance including irreversible forces and the expression is not meant to be interpreted literally.

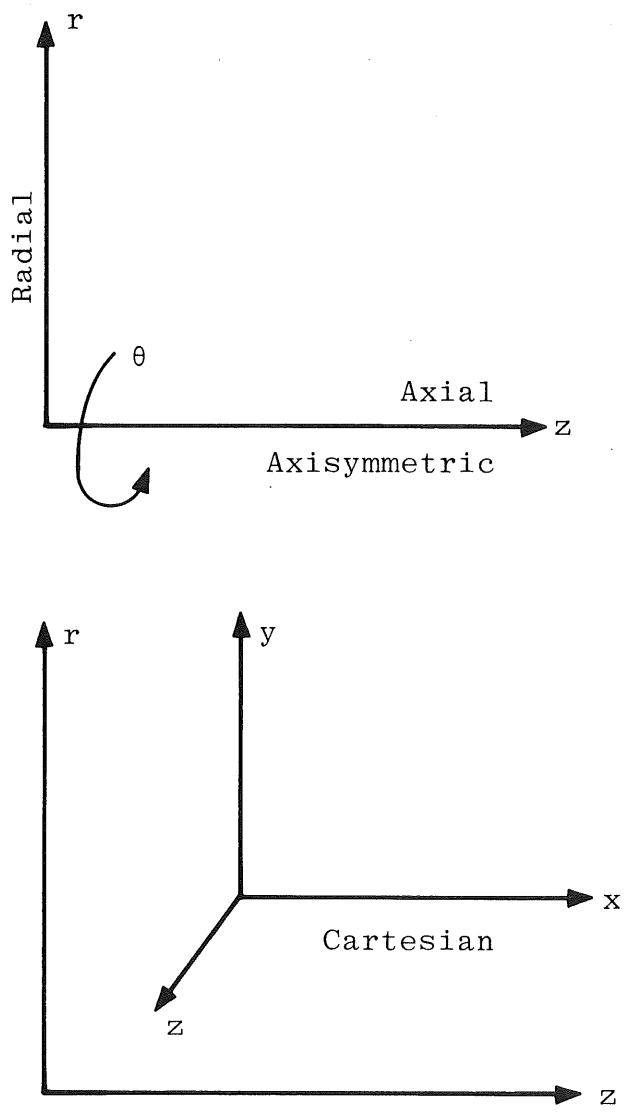


Fig. 2 Coordinate Systems

The electromagnetic influence of the Lorentz force in driving the fluid is represented explicitly as $\bar{j}x\bar{B}$ in the momentum equation and $\bar{j}\cdot\bar{E}$ in the energy equation, where $\bar{j}$, $\bar{B}$ and $\bar{E}$ represent the current, magnetic induction and electric field vectors respectively. Equations (34) through (36) contain momentum and energy convection, pressure, gravitational, viscous and electromagnetic forces and the reversible and irreversible work performed by these same forces.

Total energy per unit mass is composed of internal and kinetic energy (assuming $p = \rho RT$):

$$e = \frac{1}{\gamma-1}\cdot\left(\frac{p}{\rho}\right)+\left(\frac{u^2+v^2}{2}\right) \qquad (37)$$

$$i = \frac{1}{\gamma-1}\cdot\left(\frac{p}{\rho}\right) \qquad (38)$$

Equations (33) through (38) represent a set of coupled nonlinear partial differential equations which govern the behavior of a conducting, viscous perfect gas. Incorporating Stoke's Law, (stress proportional to the rate of strain) for laminar flow, in the form of constitutive relations (39) through (42), the system of equations becomes what is commonly referred to as the Navier-Stokes equations.

$$\tau_{rr} = -\left[2\cdot\mu\frac{\delta}{\delta r}(v)-\frac{2}{3}\cdot\mu\left\{\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(r^{\alpha}\cdot v)+\frac{\delta}{\delta z}(u)\right\}\right] \qquad (39)$$

$$\tau_{zz} = -\left[2\cdot\mu\frac{\delta}{\delta z}(u)-\frac{2}{3}\cdot\mu\left\{\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(r^{\alpha}\cdot v)+\frac{\delta}{\delta z}(u)\right\}\right] \qquad (40)$$

$$\tau_{\theta\theta} = -\left[2\cdot\mu\frac{v}{r}-\frac{2}{3}\cdot\mu\left\{\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(r^{\alpha}\cdot v)+\frac{\delta}{\delta z}(u)\right\}\right] \qquad (41)$$

$$\tau_{rz} = -\mu\left[\frac{\delta}{\delta r}(u)+\frac{\delta}{\delta z}(v)\right] \qquad (42)$$

or for turbulent flow:

$$\tau_{rz} = -(\mu+\mu_E)\left[\frac{\delta}{\delta r}(u)+\frac{\delta}{\delta z}(v)\right] \qquad (43)$$

2.3 Problems of High Magnetic Reynolds Number

When considering problems of high magnetic Reynolds number and significant, induced magnetic induction, the Lorentz force ($\vec{j}x\vec{B}$) may be replaced with the aid of Maxwell's equations as follows:

$$\vec{j}x\vec{B} = \frac{1}{\mu}(\nabla\cdot\vec{B})\cdot\vec{B} \qquad (44)$$

Incorporating this term implicitly in the form of a magneto-stress tensor, the magneto-stress elements become:

$$\tau_{rr} = \left\{\frac{B_r^2}{\mu_p}\right\} \qquad (45)$$

$$\tau_{zz} = \left\{\frac{B_z^2}{\mu_p}\right\} \qquad (46)$$

$$\tau_{\theta\theta} = \left\{\frac{B_\theta^2}{\mu_p}\right\} \qquad (47)$$

$$\tau_{rz} = \left\{\frac{B_r\cdot B_z}{\mu_p}\right\} \qquad (48)$$

which are added to the viscous stress elements.

The magnetic induction equation has three components yielding the induced fields in the azimuthal, radial and axial directions, respectively (with zero Hall current):

$$\frac{\delta}{\delta t}(B_\theta)-\frac{\delta}{\delta z}(B_\theta\cdot u)-\frac{\delta}{\delta r}(B_\theta\cdot v) = \frac{\delta}{\delta r}\left[\frac{1}{\sigma}\cdot\frac{1}{r^\alpha}\frac{\delta}{\delta r}\left(\frac{r^\alpha\cdot B_\theta}{\mu_p}\right)\right]+\frac{\delta}{\delta z}\left[\left(\frac{1}{\sigma}\right)\frac{\delta}{\delta z}\left(\frac{B_\theta}{\mu_p}\right)\right] \qquad (49)$$

$$\frac{\delta}{\delta t}(B_r)-\frac{\delta}{\delta z}(B_r\cdot u)+\frac{\delta}{\delta z}(B_z\cdot v) = +\frac{\delta}{\delta r}\left[\left(\frac{1}{\sigma}\cdot\frac{1}{r^{\alpha}}\right)\frac{\delta}{\delta r}\left(\frac{r^{\alpha}\cdot B_r}{\mu_p}\right)\right]+\frac{\delta}{\delta z}\left[\left(\frac{1}{\sigma}\frac{\delta}{\delta z}\left(\frac{B_r}{\mu_p}\right)\right)\right] \quad (50)$$

$$\frac{\delta}{\delta t}(B_z)+\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(r^{\alpha}\cdot u\cdot B_r)-\frac{1}{r^{\alpha}}\frac{\delta}{\delta r}(r^{\alpha}\cdot v\cdot B_z) = \frac{\delta}{\delta r}\left[\left(\frac{1}{\sigma}\frac{1}{r^{\alpha}}\right)\frac{\delta}{\delta r}\left(\frac{r^{\alpha}\cdot B_z}{\mu_p}\right)\right]$$

$$+\frac{\delta}{\delta z}\left[\left(\frac{1}{\sigma}\frac{\delta}{\delta z}\left(\frac{B_z}{\mu_p}\right)\right)\right] \quad (51)$$

Since this program is two-dimensional, all derivatives in the azimuthal direction have been neglected.

In equation (52), the hydrostatic and magnetic pressure were added to give the true pressure of the medium.

$$p = p+\left\{\left(\frac{B_r^2}{2\mu_p}+\frac{B_z^2}{2\mu_p}+\frac{B_\theta^2}{2\mu_p}\right)\right\} \quad (52)$$

If $\bar{j}x\bar{B}$ and $\bar{j}\cdot\bar{E}$ appear in the momentum and energy equations, then the stress tensor and pressure term do not contain the magnetic components and equations (49) through (51) need not be solved. If the magneto-stress terms are employed, then $\bar{j}x\bar{B}$ and $\bar{j}\cdot\bar{E}$ do not appear explicitly in the momentum and energy equations and currents and electric fields are not (necessarily) computed.

2.4 Problems of Low Magnetic Reynolds Number

Calculation of the electric fields and currents is developed from the solution of the elliptic partial differential equation (PDE):

$$\frac{\delta}{\delta z}\left(\frac{\delta}{\delta z}(F)\right)+\frac{\delta}{\delta r}\left(\frac{\delta}{\delta r}(F)\right)+A\frac{\delta}{\delta z}(F)+B\frac{\delta}{\delta r}(F)+C = 0 \quad (53)$$

where F represents either the electric potential or the current stream function (ϕ or Ψ), and coefficients A, B and C are functions of u, v, σ, β and $\bar{B}$. Equation (53) was derived from Maxwell's relations.

$$\nabla x \vec{E} = -\frac{\delta}{\delta t}(B) \simeq 0 \qquad (54)$$

and neglecting the rate of change of charge density

$$\nabla \cdot \vec{j} = 0 \qquad (55)$$

The derivation of this PDE and its coefficients follows.

A scalar potential is defined such that its gradient yields components of the electric field:

$$\vec{E} = -\nabla\phi \qquad (56)$$

consistent with equation (57)

$$-\nabla x \nabla\phi = 0 \qquad (57)$$

Employing Ohm's Law, the current is found to be

$$\vec{j} = \sigma(\vec{E} + \vec{v} x \vec{B}) - \frac{\beta}{|\bar{B}|}(\bar{j} X \bar{B}) \qquad (58)$$

where the first term represents the sum of the applied and induced currents resulting from the electric field and the second term is the Hall current.

Expressing Ohm's Law through a tensor conductivity:

$$\vec{j} = \bar{\bar{\sigma}} \cdot \vec{E} \qquad (59)$$

the components of current take the form:

$$j_z = \frac{\sigma}{1+\beta^2}\left[(E_z + vB) - \beta(E_r - uB)\right] \qquad (60)$$

$$j_r = \frac{\sigma}{1+\beta^2}[\beta(E_z+vB)+(E_r-uB)] \qquad (61)$$

where

j_r, j_z = r and z components of current

u, v = r and z components of particle velocity

E_r, E_z = r and z components of electric field

σ = scalar conductivity

β = Hall parameter

B = θ component of the magnetic induction*

and from Equation (56)

$$E_z = -\frac{\delta}{\delta z}(\phi) \qquad E_r = -\frac{\delta}{\delta r}(\phi) \qquad (62)$$

Substituting Equations (60), (61), and (62) into Equation (55), Equation (63) results:

$$\frac{\delta}{\delta z}\left(\frac{\delta}{\delta z}(\phi)\right)+\frac{\delta}{\delta r}\left(\frac{\delta}{\delta r}(\phi)\right)+\left[\frac{1}{\sigma_\dagger}\frac{\delta}{\delta z}(\sigma_\dagger)+\beta\frac{1}{\sigma_\dagger}\frac{\delta}{\delta r}(\sigma_\dagger)+\frac{\delta}{\delta r}(\beta)\right]\frac{\delta}{\delta z}(\phi)$$

$$+\left[\frac{1}{\sigma_\dagger}\frac{\delta}{\delta r}(\sigma_\dagger)-\beta\frac{1}{\sigma_\dagger}\frac{\delta}{\delta z}(\sigma_\dagger)-\frac{\delta}{\delta z}(\beta)\right]\frac{\delta}{\delta r}(\phi)+\left[vB+\beta uB\right]\frac{1}{\sigma_\dagger}\frac{\delta}{\delta z}(\sigma_\dagger)$$

$$-\frac{\delta}{\delta z}(vB+\beta uB)-\left[uB-\beta vB\right]\frac{1}{\sigma_\dagger}\frac{\delta}{\delta r}(\sigma_\dagger)+\frac{\delta}{\delta r}(uB-\beta vB) = 0 \qquad (63)$$

where

$$\sigma_\dagger = \frac{\sigma}{1+\beta^2} \qquad (64)$$

---

*r and z magnetic fields are not treated since the MHD generator modeled in Section (4) does not require it.

From Equation (55), one may define a current stream function Ψ as

$$j_z = \frac{\delta}{\delta r}(\Psi) \qquad j_r = -\frac{\delta}{\delta z}(\Psi) \tag{65}$$

Employing Equations (54) and (58), Equation (66) is developed:

$$\frac{\delta}{\delta z}\left(\frac{\delta}{\delta z}(\Psi)\right) + \frac{\delta}{\delta r}\left(\frac{\delta}{\delta r}(\Psi)\right) + \left[-\frac{1}{\sigma_+}\frac{\delta}{\delta z}(\sigma_+) + \beta\frac{1}{\sigma_+}\frac{\delta}{\delta r}(\sigma_+) + \frac{\delta}{\delta r}(\beta)\right]\frac{\delta}{\delta z}(\Psi) +$$

$$\left[-\frac{1}{\sigma_+}\frac{\delta}{\delta r}\left(\frac{\delta}{\delta r}\right) - \beta\frac{1}{\sigma_+}\frac{\delta}{\delta z}(\sigma_+) + \frac{\delta}{\delta z}(\beta)\right]\frac{\delta}{\delta r}(\Psi) + \sigma\left[\left(\frac{\delta}{\delta z}(Bu) + \frac{\delta}{\delta r}(Bv)\right)\right] = 0 \tag{66}$$

2.5 HULL Finite Difference Equations

A method developed by Daniel Matuska for computing hydrodynamic properties of a fluid was employed. A discussion of the HULL finite difference technique appears in Appendix (A); the salient features are outlined below:

Calculations are performed in two phases: phase I, integrating the "Lagrangian terms" (coordinate system fixed to the fluid element) and phase II treating the convective terms by transporting mass.

A grid is initially generated as shown in Figure (3). Parallel, although not necessarily equally spaced lines are constructed in both the r and z directions. These grid lines form a mesh with elements or cells defined by the four grid lines bordering it. Each cell is assigned an index value in much the same manner that elements of a matrix are assigned identification. The lower left-hand boundary cell has indices of i=1, j=1 and incrementing values of i as one marches in the vertical (r) direction or incrementing values of j as one marches in the axial (z) direction. There are certain hydrodynamic (thermodynamic) variables assigned to each cell initially, with updated values of these variables stored in the ensuing calculations. These variables are density, axial velocity, radial velocity and total energy (magnetic and electric fields are added later). Other properties, such as pressure or internal energy, can be computed directly from these parameters. In phase I calculations, values of ρ, u, v and e at the boundary of the cell are needed; therefore, indices: $i,j-\frac{1}{2}$; $i-\frac{1}{2},j$; $i,j+\frac{1}{2}$; and $i+\frac{1}{2},j$ refer to such values (see Figure (4)).

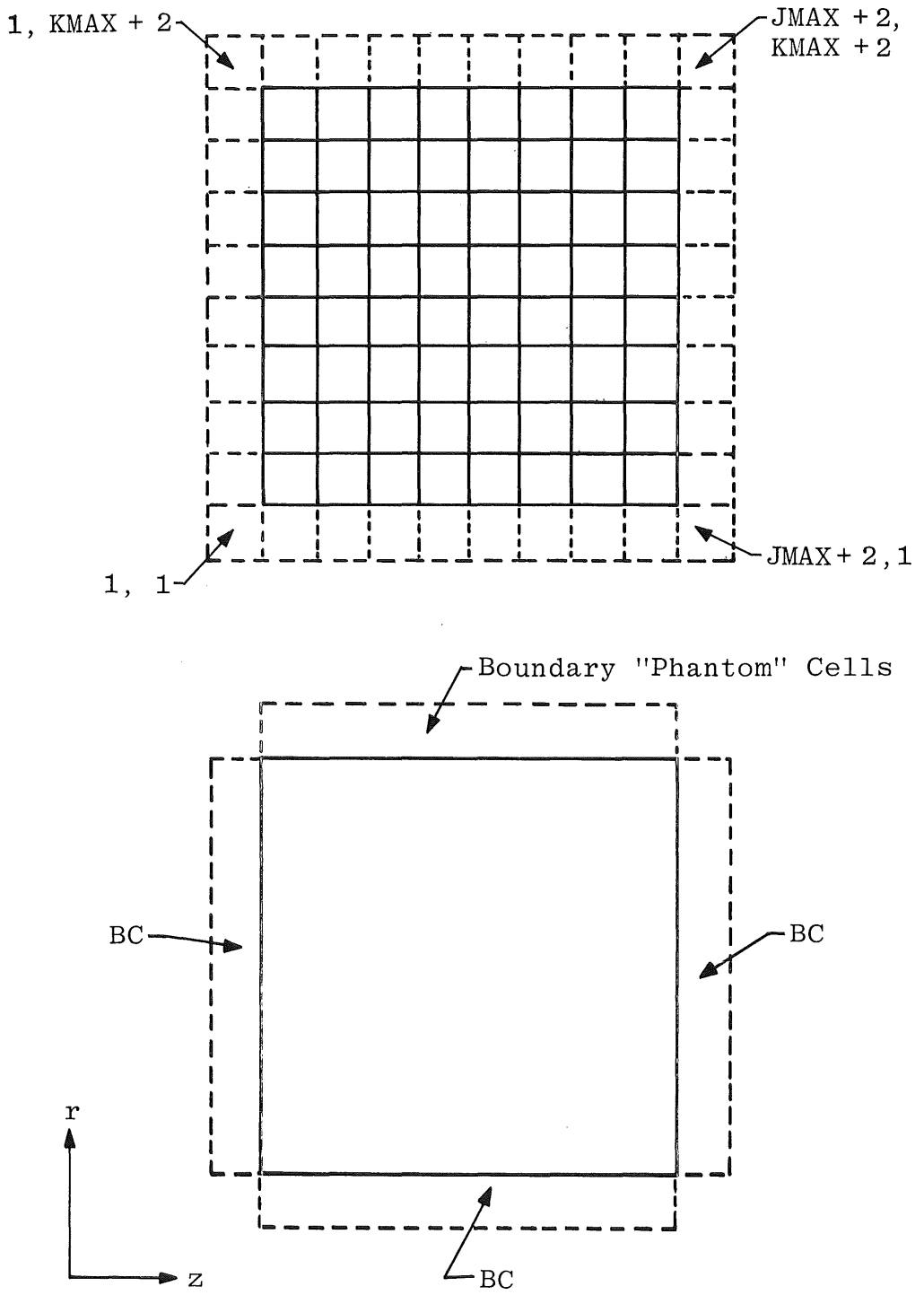


Fig. 3 Grid Setup

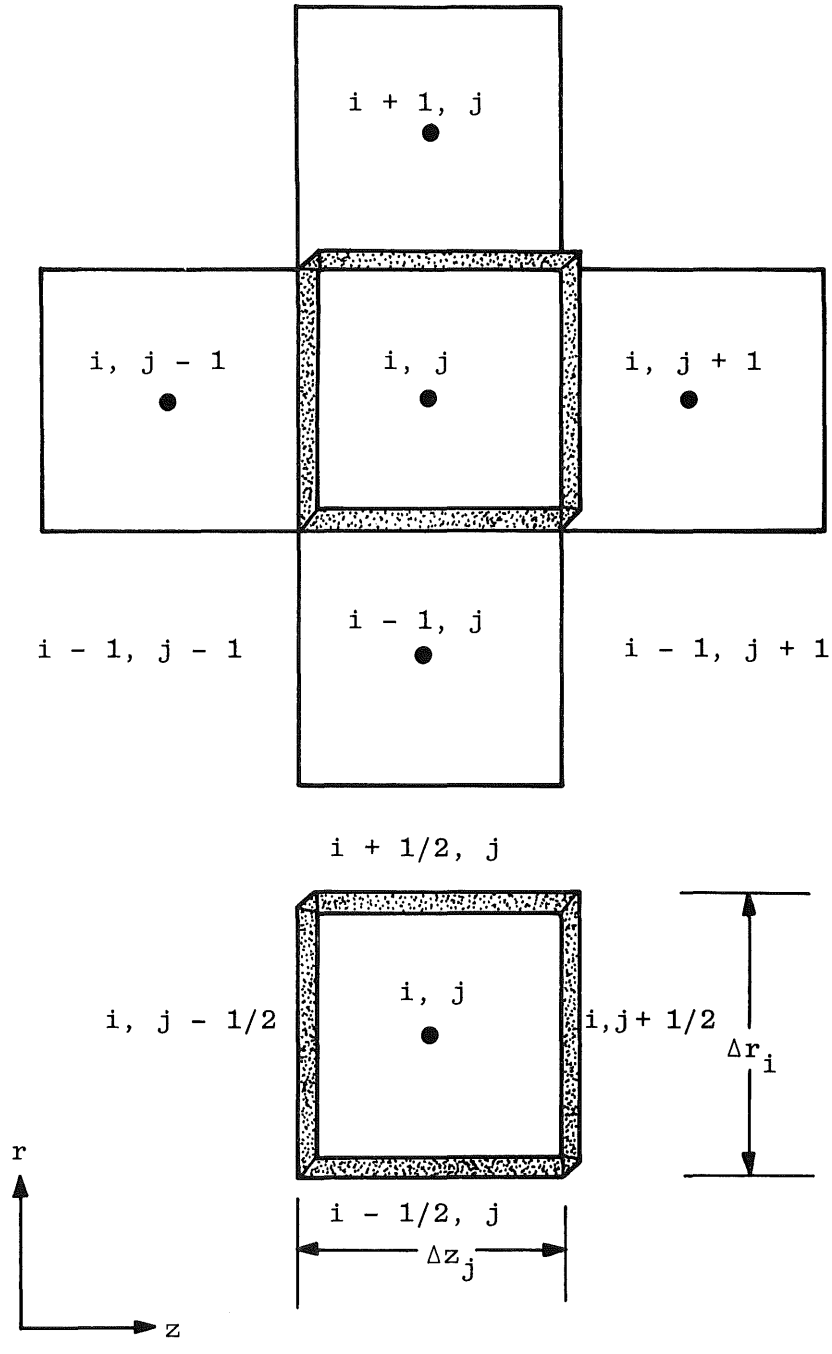


Fig. 4 Subscript Notation for Cell Identification

Matuska solved Equations (18) through (20) and (23), excluding the viscous, magnetic and heat conduction terms, whereas the development of a numerical solution to equations (18) through (29) in their entirety makes up the subject of this study.

Employing those numerical features characterizing HULL which distinguish its methodology from other finite-difference techniques, calculations are:

(I) time and space centered, analogous to a "predictor-corrector" integration.

(II) performed in two phases; phase I: calculating the change in momentum and energy in a Lagrangian reference frame (no convection) (Figure (5)) and phase II: employing the "donor-receivor" technique where mass, momentum and energy are transported (convected) between neighboring cells.

Figure (6) illustrates a cell with indices assigned at the cell center and four cell interfaces. The values of ρ, u, v and e (or p) are known at t(n). The procedure for determining ρ, u, v, and e at t(n+1) is as follows:

Referring to Figure (6), ρ, u, v and p

(1) are defined at each interface based on cell center values at t(n), Figure (6a).

(2) are updated to $t(n+\frac{1}{2})$ by "predicting" values based on the conservation equations - time centering (Figure (6b)).

(3) at cell centers are computed by again integrating using the interface values - space centering.

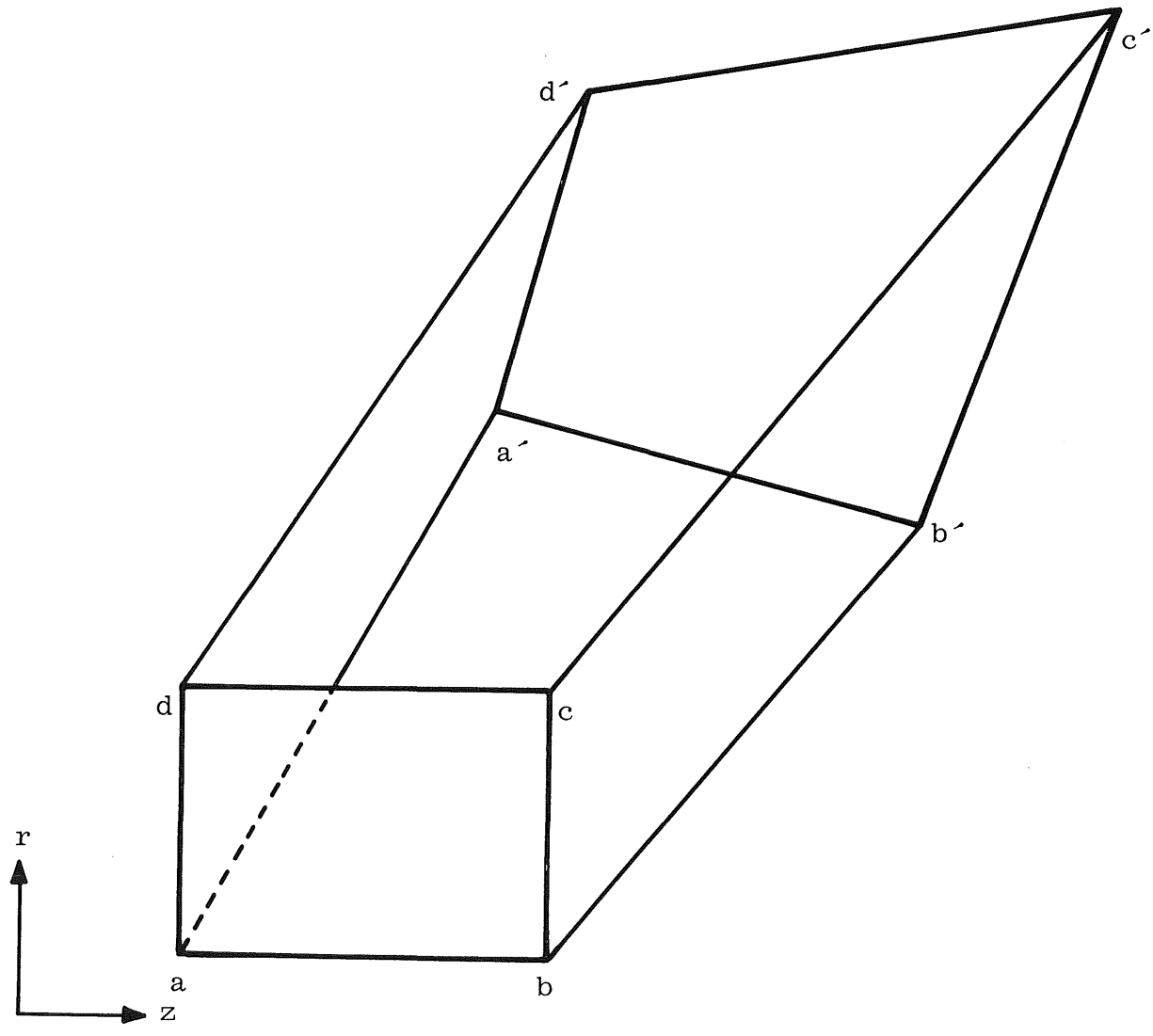


Fig. 5 Lagrangian Integration

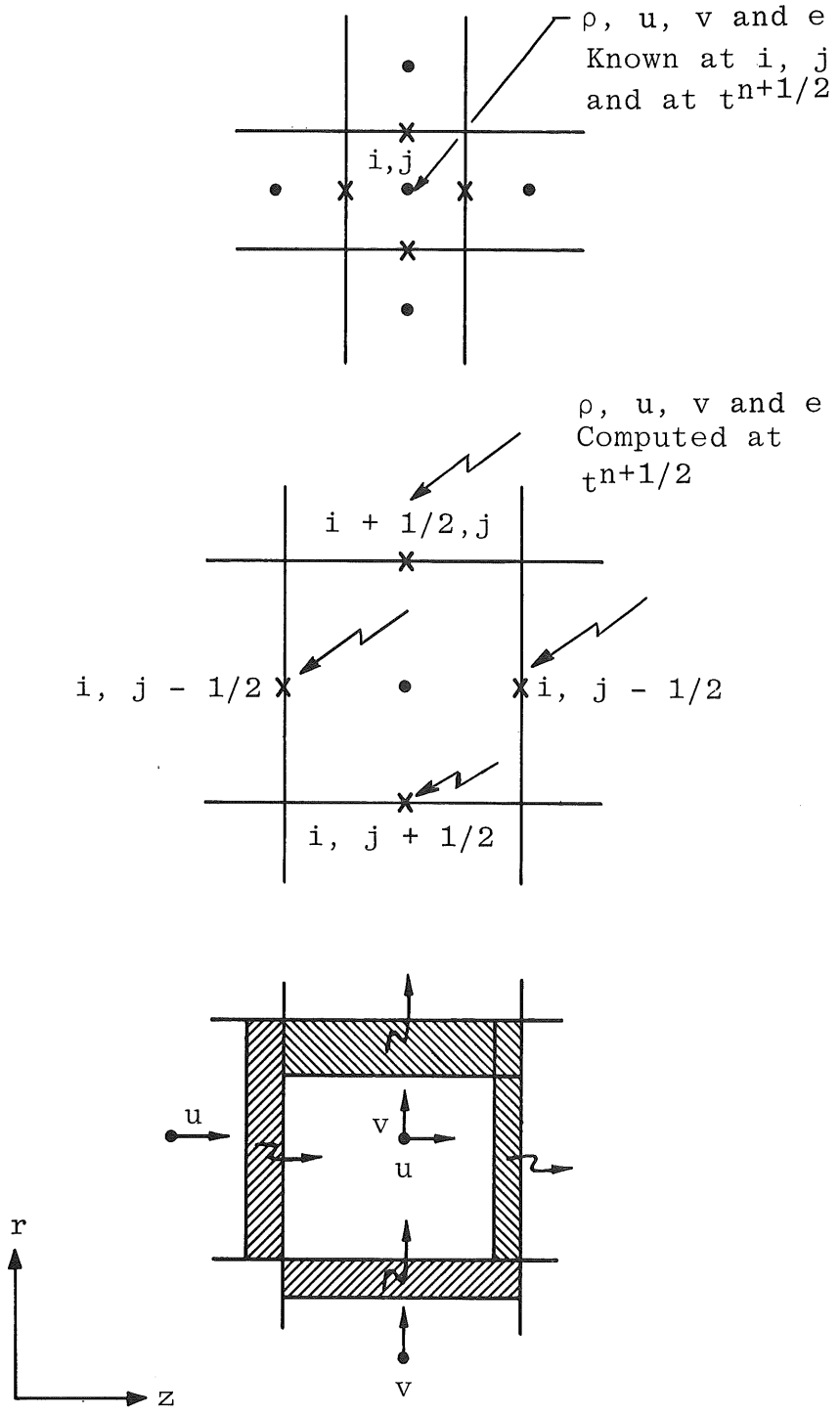


Fig. 6 Integration Technique of HULL

(4) at t(n+1) are employed to flux mass from cell to cell and thus restore the distorted Lagrangian mesh (Figure (6c)) to its original position.

The fundamental purpose of time and space centering is to preserve numerical stability, especially in regions of small hydrodynamic gradients. Further, by employing the donor-receiver technique in phase II and "re-zoning" the displaced Lagrangian mesh back to its original position, the calculation remains Eulerian in nature.

2.6 Curved Boundaries

Conditions for a solid boundary are represented by Equations (30) to (32). If the body is curved, as is shown in Figure (7), the angle of curvature is determined over segments of the curve and the unit normal vector is evaluated over the segment chord. Thus, cells lying on the solid boundary are "oriented" so that the bodies true streamline is reflected in the calculation.

2.7 Finite Difference Equations (FDEs)

An introductory explanation of the HULL FDEs appear in Appendix (A). This section examines the complete set of equations, including viscous, thermal, magnetic and electric terms all in finite difference form.

Phase I (Lagrangian Frame of Reference)

Referring to Figure (4) where the indices i,j are defined, calculations made in a Lagrangian frame of reference consists of traveling with the moving fluid or mass particles or in the case of this program, traveling with cells (or grids) of fixed mass. In Equation (69) the cell mass is computed by taking a circular cut of the cell from $(r(i+\frac{1}{2}),r(i-\frac{1}{2}))$ to

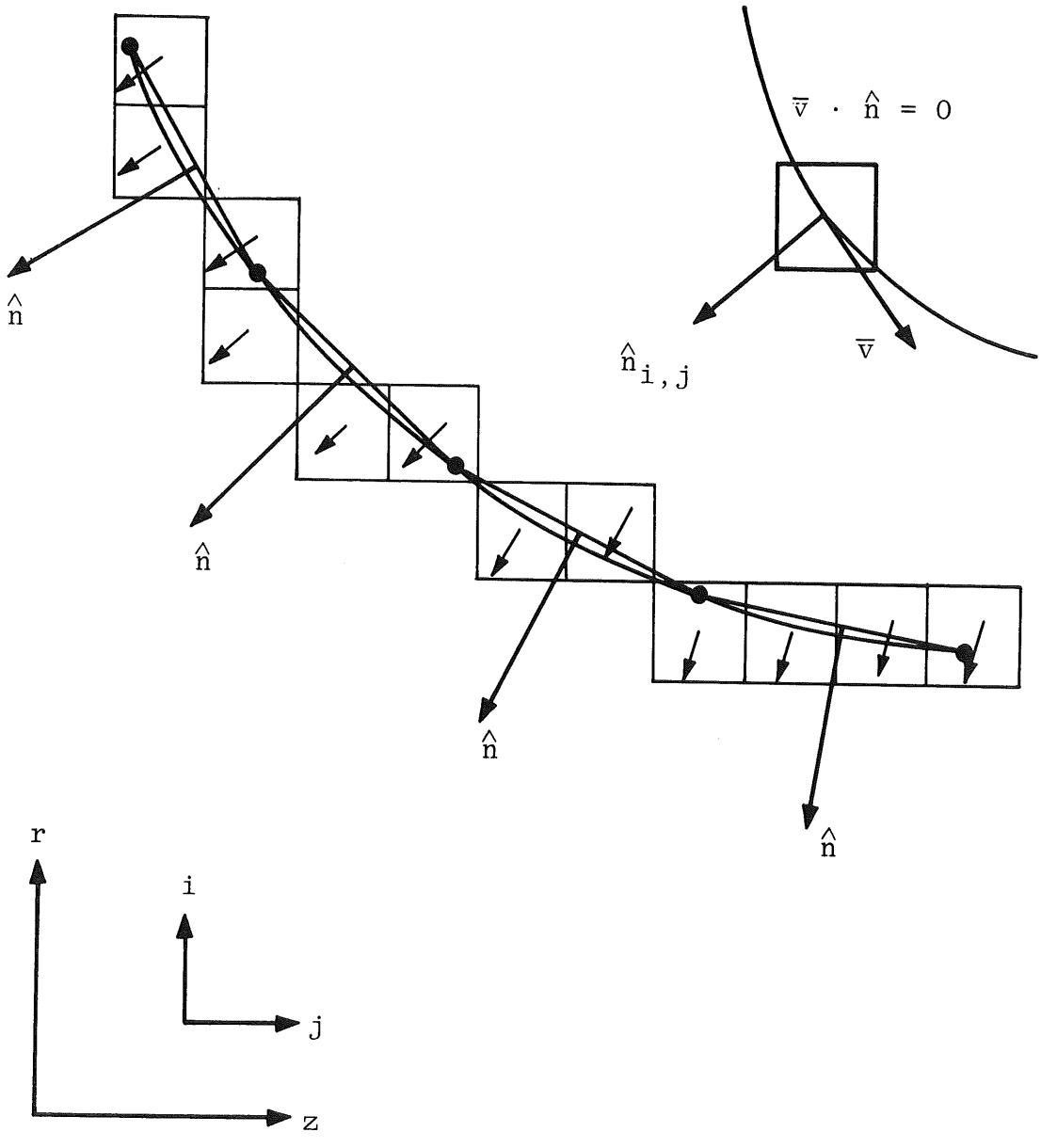


Fig. 7 Oblique or Curvilinear Boundary Conditions

the origin (see Figure (8)). In Cartesian coordinates, the volume sweep consumes the cell area x unit depth.

$$r_{i-\frac{1}{2}} = r_i - \frac{\Delta r_i}{2} \tag{67}$$

$$r_{i+\frac{1}{2}} = r_i + \frac{\Delta r_i}{2} \tag{68}$$

$$M^n_{i,j} = \rho^n_{i,j} \cdot \pi \cdot (r^2_{i+\frac{1}{2}} - r^2_{i-\frac{1}{2}}) \Delta z_j \tag{69}$$

Equations (70) and (71) reveal the average densities at the cell interface

$$\rho^n_{i+\frac{1}{2},j} = \frac{(M^n_{i,j} + M^n_{i+1,j})}{\pi (r^2_{i+3/2} - r^2_{i-\frac{1}{2}}) \Delta z_j} \tag{70}$$

$$\rho^n_{i,j+\frac{1}{2}} = \frac{(M^n_{i,j} + M^n_{i,j+1})}{\pi (r^2_{i+\frac{1}{2}} - r^2_{i-\frac{1}{2}}) (\Delta z_j + \Delta z_{j+1})} \tag{71}$$

at time (n). In order to maintain stability and convergence in all calculations, integrations must be spatially and temporally centered. Thus in the fashion of a predictor-corrector integration, values are computed at time (n+½) and at i+½, j+½, i-½, j-½ and these values used in the integration to compute fluid properties at the center of each cell and at time (n+1). Equations (72) and (73) generate cell interface values of density at time (n+½).

$$\rho^{n+\frac{1}{2}}_{i+\frac{1}{2},j} = \rho^n_{i+\frac{1}{2},j} \left\{ 1 - \frac{\Delta t^{n+\frac{1}{2}} (r_{i+1} \cdot v^n_{i+1,j} - r_i \cdot v^n_{i,j})}{2 r_{i+\frac{1}{2}} (r_{i+1} - r_i)} \right\} \tag{72}$$

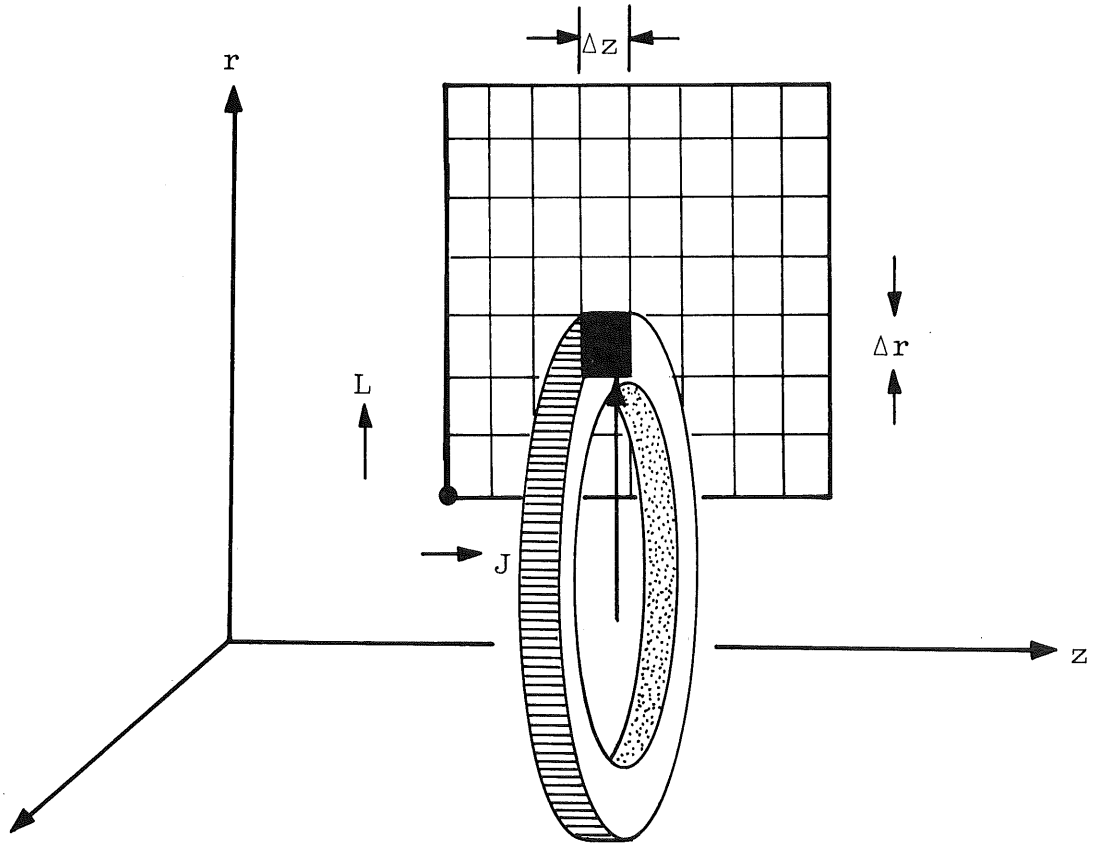


Fig. 8 Volume Element of a Cell

$$\rho^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} = \rho^{n}_{i,j+\frac{1}{2}}\{1 - \frac{\Delta t^{n+\frac{1}{2}}(u^{n}_{i,j+1} - u^{n}_{i,j})}{2(z_{j+1} - z_{j})}\} \qquad (73)$$

In Cartesian coordinates the mass and density is given by:

$$M^{n}_{i,j} = \rho^{n}_{i,j}\Delta r_{i}\Delta z_{j} \qquad (74)$$

and

$$\rho^{n}_{i+\frac{1}{2},j} = \frac{(M^{n}_{i,j} + M^{n}_{i+1,j})}{\Delta r_{i}\Delta z_{j}} \qquad (75)$$

However, as r goes to infinity, ρ (cylindrical) approaches ρ (Cartesian) and therefore Equations (69) through (73) are sufficient for both coordinate systems.

A time dependent equation for pressure, based on the conservation of mass, momentum and energy (Appendix (B)) includes contributions from pressure induced expansion (or compression), ohmic heating and viscous dissipation. All magnetic and electric terms, such as ohmic heating, may be represented either by a magnetic stress tensor employing the second-order elliptic magnetic induction equation, as derived from Maxwell's relations or by solution to a second-order elliptic stream current or potential equation as described on page 32. In the first case, currents are generated by the induced magnetic fields according to Equation (22) and thus are contained implicitly in the "divergence" of a magneto-stress tensor. In the second case, currents are explicitly defined through the use of potential or (current) stream functions and Ohm's Law. Either the induction equation or the stream function/potential equation may be employed as each equally represents the

influence of electric and magnetic effects on the flow field. (Later in this section a more detailed discussion of the calculation of currents and the electric field can be found.)

The fundamental purpose of time and space-centering all calculations in Phase I, as developed by Matuska, was to avoid instabilities resulting from forces creating small momentum gradients.† While p and j x $\overline{B}$ forces create severe gradients, viscous forces tend to diffuse momentum and do not pose a significant threat to stability as compared with other MHD forces.* It is primarily for this reason that pressure and electromagnetic terms are time and space centered, whereas viscous terms are not. Thermal conduction is also neglected at this stage because of its relatively smaller contribution to the momentum and energy equations over a time step. Computing the pressure at the cell interface at time $(n+\frac{1}{2})$ (see Appendix (B)):

$$p^{n+\frac{1}{2}}_{i+\frac{1}{2},j} = p^{n}_{i+\frac{1}{2},j}\left\{1+\frac{\Delta t^{n+\frac{1}{2}}\gamma\left(r_{i,1}\cdot v^{n}_{i+1,j}-r_{i}\cdot v^{n}_{i,j}\right)}{2r_{i+\frac{1}{2}}\left(r_{i+1}-r_{i}\right)}\right\}$$

$$+(\gamma-1)\left(j^{n}_{r_{i+\frac{1}{2},j}}\cdot j^{n}_{r_{i+\frac{1}{2},j}}+j^{n}_{z_{i+\frac{1}{2},j}}\cdot j^{n}_{z_{i+\frac{1}{2},j}}\right)/\sigma^{n}_{i+\frac{1}{2},j} \qquad (76)$$

$$p^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} = p^{n}_{i,j+\frac{1}{2}}\left\{1+\frac{\Delta t^{n+\frac{1}{2}}\gamma\left(u^{n}_{i,j+1}-u^{n}_{i,j}\right)}{2\left(z_{j+1}-z_{j}\right)}\right\}$$

$$+(\gamma-1)\left(j^{n}_{r_{i,j+\frac{1}{2}}}\cdot j^{n}_{r_{i,j+\frac{1}{2}}}+j^{n}_{z_{i,j+\frac{1}{2}}}\cdot j^{n}_{z_{i,j+\frac{1}{2}}}\right)/\sigma^{n}_{i,j+\frac{1}{2}} \qquad (77)$$

---

*provided the time step is bounded (Eqns (16) and (17))

†Instability developing from severe gradients is eliminated by fluxing (Phase II).

If the current stream function is employed, the space-centered currents and electric fields are defined at time (n) by:

$$j^n_{z_{i,j}} = + \frac{\delta}{\delta r}(\psi^n) = \frac{\psi^n_{i+1,j} - \psi^n_{i-1,j}}{2\Delta r_i} \quad (78)$$

$$j^n_{r_{i,j}} = -\frac{\delta}{\delta z}(\psi^n) = -\frac{\psi^n_{i,j+1} - \psi^n_{i,j-1}}{2\Delta z_j} \quad (79)$$

$$E^n_{z_{i,j}} = (j^n_{z_{i,j}} + \beta^n_{i,j} j^n_{r_{i,j}})/\sigma^n_{i,j} - v^n_{i,j} B^n_{\theta_{i,j}} \quad (80)$$

$$E^n_{r_{i,j}} = (j^n_{r_{i,j}} - \beta^n_{i,j} j^n_{z_{i,j}})/\sigma^n_{i,j} + u^n_{i,j} B^n_{\theta_{i,j}} \quad (81)$$

If the electric potential is used, the space-centered currents and electric fields become at time (n):

$$E^n_{z_{i,j}} = -\frac{\delta}{\delta z}(\phi^n) = -\frac{\phi^n_{i,j+1} - \phi^n_{i,j-1}}{2\Delta z_j} \quad (82)$$

$$E^n_{r_{i,j}} = -\frac{\delta}{\delta r}(\phi^n) = -\frac{\phi^n_{i+1,j} - \phi^n_{i-1,j}}{2\Delta r_i} \quad (83)$$

$$j^n_{z_{i,j}} = \sigma^n_{i,j}[(E^n_{z_{i,j}} + v^n_{i,j} B^n_{\theta_{i,j}}) - \beta^n_{i,j}(E^n_{r_{i,j}} - u^n_{i,j} B^n_{\theta_{i,j}})] \quad (84)$$

$$j^n_{r_{i,j}} = \sigma^n_{i,j}[\beta^n_{i,j}(E^n_{r_{i,j}} + v^n_{i,j} B^n_{\theta_{i,j}}) + (E^n_{r_{i,j}} - u^n_{i,j} B^n_{\theta_{i,j}})] \quad (85)$$

The choice of using either the stream function or potential is usually dictated by the electrical boundary conditions. If the voltage (or potential) at the electrodes is known, the potential is employed. If the external currents at the electrodes are known, then a stream function

is used. Further, since the potential is constant on a conductor and the stream function is constant on an insulator, defining infinity for a particular generator might strongly influence the choice of one method over the other.

The values of the currents at the cell interfaces are computed by using the values of ϕ and Ψ of the two cells adjoining at the interface and employing the velocities, conductivity, Hall parameter and magnetic fields evaluated at the interface. The relation between the stream function and potential at the cell center and time (n) becomes:

$$\Psi^n_{i,j} = \Psi^n_{i,j-1} - (j^n_{r_{i,j}} + j^n_{r_{i,j-\frac{1}{2}}})/\{2\cdot(z_j - z_{j-1})\} \qquad (86)$$

$$\phi^n_{i,j} = \phi^n_{i,j-1} - (E^n_{r_{i,j}} + E^n_{r_{i,j-\frac{1}{2}}})/\{2\cdot(z_j - z_{j-1})\} \qquad (87)$$

If the magnetic induction equation is employed ($Re_m >> 1$), the magnetic stress elements become:

$$\tau^n_{rr_{i+1,j}} = -\frac{B^n_{r_{i+1,j}} \cdot B^n_{r_{i+1,j}}}{\mu_p} \qquad (88)$$

$$\tau^n_{zz_{i,j+1}} = -\frac{B^n_{z_{i,j+1}} \cdot B^n_{z_{i,j+1}}}{\mu_p} \qquad (89)$$

$$\tau^n_{\theta\theta_{i+1,j}} = -\frac{B^n_{z_{i,j+1}} \cdot B^n_{z_{i,j+1}}}{\mu_p} \qquad (90)$$

$$\tau^n_{rz_{i+1,j+1}} = -\frac{2B^n_{r_{i+1,j+1}} + B^n_{r_{i+1,j}} + B^n_{r_{i,j+1}}}{4\mu_p} \cdot \frac{2B^n_{z_{i+1,j+1}} + B^n_{z_{i+1,j}} + B^n_{z_{i,j+1}}}{4\mu_p} \qquad (91)$$

$$\tau^{n}_{rr_{i,j}} = -\frac{B^{n}_{r_{i,j}} \cdot B^{n}_{r_{i,j}}}{\mu_p} \qquad (92)$$

$$\tau^{n}_{zz_{i,j}} = -\frac{B^{n}_{z_{i,j}} \cdot B^{n}_{z_{i,j}}}{\mu_p} \qquad (93)$$

$$\tau^{n}_{\theta\theta_{i,j}} = -\frac{B^{n}_{\theta_{i,j}} \cdot B^{n}_{\theta_{i,j}}}{\mu_p} \qquad (94)$$

$$\tau^{n}_{rz_{i+1,j+1}} = -\frac{B^{n}_{r_{i,j}} \cdot B^{n}_{z_{i,j}}}{\mu_p} \qquad (95)$$

The Lagrangian velocities at the interface at time $(n+\frac{1}{2})$ may now be computed:

$$u^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} = u^{n}_{i,j+\frac{1}{2}} - \frac{\Delta t^{n+\frac{1}{2}}}{2\rho^{n+\frac{1}{2}}_{i,j+\frac{1}{2}}}\left(\frac{p^{n}_{i,j+1} - p^{n}_{i,j}}{z_{j+1} - z_j}\right) - g_z \frac{\Delta t^{n+\frac{1}{2}}}{2} - \frac{\Delta t^{n+\frac{1}{2}}}{2\rho^{n+\frac{1}{2}}_{i,j+\frac{1}{2}}}\left\{\frac{\tau^{n}_{zz_{i,j+1}} - \tau^{n}_{zz_{i,j}}}{\Delta z_{j+1}}\right.$$

$$\left. + \frac{r_{i+1}\tau^{n+\frac{1}{2}}_{rz_{i+1,j+1}} - r_i \tau^{n}_{rz_{i,j}}}{r_{i+\frac{1}{2}} \cdot \Delta r_{i+1}}\right\} + \frac{\Delta t^{n+\frac{1}{2}}}{2\rho^{n+\frac{1}{2}}_{i,j+\frac{1}{2}}} j_{r_{i,j+p}} B^{n+\frac{1}{2}}_{\theta_{i,\frac{1}{2},j}} \qquad (96)$$

$$v^{n+\frac{1}{2}}_{i+\frac{1}{2},j} = -\frac{\Delta t^{n+\frac{1}{2}}}{2\rho^{n+\frac{1}{2}}_{i+\frac{1}{2},j}}\left(\frac{p^{n+1}_{i+1,j} - p^{n}_{i,j}}{r_{i+1} - r_i}\right) - g_r \frac{\Delta t^{n+\frac{1}{2}}}{2} - \frac{\Delta t^{n+\frac{1}{2}}}{2\rho^{n+\frac{1}{2}}_{i+\frac{1}{2},j}}\left\{\frac{\tau^{n}_{rz_{i+1,j+1}} - \tau^{n}_{rz_{i,j}}}{\Delta z_{j+1}}\right.$$

$$\left. + \frac{r_{i+1}\tau^{n}_{rr_{i+1,j}} - r_i \tau^{n}_{rr_{i,j}}}{r_{i+\frac{1}{2}} \cdot \Delta r_{i+1}} - \frac{\tau^{n+\frac{1}{2}}_{\theta\theta_{i+\frac{1}{2},j}}}{r_{i+\frac{1}{2}}}\right\} - \frac{\Delta t^{n+\frac{1}{2}}}{2\rho^{n+\frac{1}{2}}_{i+\frac{1}{2},j}} j^{n}_{z_{i+\frac{1}{2},j}} B^{n+\frac{1}{2}}_{\theta_{i+\frac{1}{2},j}} \qquad (97)$$

Having predicted the values of pressure, density, velocity and currents at each cell interface at time $(n+\frac{1}{2})$, the final stage of Phase I, computing u,v and e at time (n+1) (excluding convection), proceeds.

The rate of strain at each cell interface is computed based on values of u and v at time (n).

$$\varepsilon^n_{r_{i+\frac{1}{2},j}} = \frac{v^n_{i+1,j} - v^n_{i,j}}{r_{i+1} - r_i} \tag{98}$$

$$\varepsilon^n_{z_{i,j+\frac{1}{2}}} = \frac{u^n_{i,j+1} - u^n_{i,j}}{z_{j+1} - z_j} \tag{99}$$

$$\varepsilon^n_{\theta_{i+\frac{1}{2},j}} = \frac{v^n_{i+1,j} + v^n_{i,j}}{2r_{i+\frac{1}{2}}} \tag{100}$$

$$\varepsilon^n_{rz_{i+\frac{1}{2},j+\frac{1}{2}}} = \frac{u^n_{i+1,j} - u^n_{i,j}}{r_{i+1} - r_{i-\frac{1}{2}}} + \frac{v^n_{i,j+1} - v^n_{i,j}}{z_{j+1} - z_j} \tag{101}$$

$$\varepsilon^n_{i+1,j+1} = \varepsilon^n_{r_{i+\frac{1}{2},j}} + \varepsilon^n_{z_{i,j+\frac{1}{2}}} + \varepsilon^n_{\theta_{i+\frac{1}{2},j}} \tag{102}$$

Next, calculating the stress tensor elements at each cell interface at time (n):

for laminar flow:

$$\tau^n_{rr_{i+\frac{1}{2},j}} = -2\mu^n_{i+\frac{1}{2},j}\varepsilon^n_{r_{i+\frac{1}{2},j}} + \frac{2}{3}\mu^n_{i+\frac{1}{2},j}\varepsilon^n_{i+1,j+1} \tag{103}$$

$$\tau^n_{zz_{i,j+\frac{1}{2}}} = -2\mu^n_{i,j+\frac{1}{2}}\varepsilon^n_{z_{i,j+\frac{1}{2}}} + \frac{2}{3}\mu^n_{i,j+\frac{1}{2}}\varepsilon^n_{i+1,j+1} \tag{104}$$

$$\tau^n_{\theta\theta_{i+\frac{1}{2},j}} = -2\mu^n_{i+\frac{1}{2},j}\varepsilon^n_{\theta_{i+\frac{1}{2},j}} + \frac{2}{3}\mu^n_{i+\frac{1}{2},j}\varepsilon^n_{i+1,j+1} \tag{105}$$

$$\tau^n_{rz_{i+\frac{1}{2},j+\frac{1}{2}}} = -\mu^n_{i+\frac{1}{2},j+\frac{1}{2}}\varepsilon^n_{rz_{i+1,j+1}} \tag{106}$$

and for turbulent flow, the first three viscous stresses are zero and employing an eddy viscosity:

$$\tau^{n}_{rz_{i+\frac{1}{2},j+\frac{1}{2}}} = -(\mu_{i+\frac{1}{2},j+\frac{1}{2}}+\mu^{n}_{\lambda_E})\varepsilon^{n}_{rz_{i+1,j+1}} \tag{107}$$

If the magnetic induction equations are employed, the stresses become

$$\tau^{n}_{rr_{i+\frac{1}{2},j}} = -\frac{B^{n}_{r_{i+\frac{1}{2},j}} \cdot B^{n}_{r_{i+\frac{1}{2},j}}}{\mu_p} + \text{viscous component} \tag{108}$$

$$\tau^{n}_{zz_{i,j+\frac{1}{2}}} = -\frac{B^{n}_{z_{i,j+\frac{1}{2}}} \cdot B^{n}_{z_{i,j+\frac{1}{2}}}}{\mu_p} + \text{viscous component} \tag{109}$$

$$\tau^{n}_{\theta\theta_{i+\frac{1}{2},j}} = -\frac{B^{n}_{\theta_{i+\frac{1}{2},j}} \cdot B^{n}_{\theta_{i+\frac{1}{2},j}}}{\mu_p} + \text{viscous component} \tag{110}$$

$$\tau^{n}_{rz_{i+\frac{1}{2},j+\frac{1}{2}}} = -\frac{B^{n}_{r_{i+\frac{1}{2},j+\frac{1}{2}}} \cdot B^{n}_{z_{i+\frac{1}{2},j+\frac{1}{2}}}}{\mu_p} + \text{viscous component} \tag{111}$$

The change in velocities over a time step results from forces due to pressure, magnetic fields and gravity.

$$u^{n+1}_{i,j} = u^{n}_{i,j} - \frac{\Delta t^{n+\frac{1}{2}}}{\rho^{n}_{i,j}}\left\{\frac{p^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} - p^{n+\frac{1}{2}}_{i,j-\frac{1}{2}}}{\Delta z_j}\right\} - g_z \Delta t^{n+\frac{1}{2}} - \frac{\Delta t^{n+\frac{1}{2}}}{\rho^{n}_{i,j}}\left\{\frac{r_{i+\frac{1}{2}}\tau^{n}_{rz_{i-\frac{1}{2},j+\frac{1}{2}}} - r_{i-\frac{1}{2}}\tau^{n}_{rz_{i-\frac{1}{2},j-\frac{1}{2}}}}{r_i \cdot \Delta r_i}\right.$$

$$\left. + \frac{\tau^{n}_{zz_{i,j+\frac{1}{2}}} - \tau^{n}_{zz_{i,j-\frac{1}{2}}}}{\Delta z_j}\right\} + j^{n+\frac{1}{2}}_{z_{i,j}} B^{n}_{\theta_{i,j}} \frac{\Delta t^{n+\frac{1}{2}}}{\rho^{n}_{i,j}} \tag{112}$$

$$v_{i,j}^{n+1} = v_{i,j}^{n} - \frac{\Delta t^{n+\frac{1}{2}}}{\rho_{i,j}^{n}}\left\{\frac{p_{i+\frac{1}{2},j}^{n+\frac{1}{2}} - p_{i-\frac{1}{2},j}^{n+\frac{1}{2}}}{\Delta r_i}\right\} - g_r \Delta t^{n+\frac{1}{2}} - \frac{\Delta t^{n+\frac{1}{2}}}{\rho_{i,j}^{n}}\left\{\frac{r_{i+\frac{1}{2}}\tau_{rr}^{n}{}_{i+\frac{1}{2},j} - r_{i-\frac{1}{2}}\tau_{rr}^{n}{}_{i-\frac{1}{2},j}}{r_i \cdot \Delta r_i}\right.$$

$$\left. + \frac{\tau_{rz}^{n}{}_{i+\frac{1}{2},j+\frac{1}{2}} - \tau_{rz}^{n}{}_{i-\frac{1}{2},j-\frac{1}{2}}}{\Delta z_j} - \frac{\tau_{\theta\theta}^{n}{}_{i+\frac{1}{2},j} + \tau_{\theta\theta}^{n}{}_{i-\frac{1}{2},j}}{p_{i-\frac{1}{2},j+\frac{1}{2}}^{n}}\right\} + j_{z_{i,j}}^{n+\frac{1}{2}} B_{\theta_{i,j}}^{n} \frac{\Delta t^{n+\frac{1}{2}}}{\rho_{i,j}^{n}} \qquad (113)$$

The change in energy for each volume element over a time step is based on contributions from: (1) the work done by the pressure of the surroundings on the volume element, (2) the work done by viscous and/or magnetic forces on a volume element, (3) the energy input by thermal conduction into a volume element, (4) the work done by the pondermotive (Lorentz) force in driving the fluid, including Joule heating and (5) the work done by gravity. Note, once again, if the stress elements contain magnetic terms ($Re_m >> 1$) then the last terms in Equation (112) and (113) are ignored.

$$i_{i,j}^{n} = e_{i,j}^{n} - \frac{1}{2}\left(u_{i,j}^{n} \cdot u_{i,j}^{n} + v_{i,j}^{n} \cdot v_{i,j}^{n}\right) \qquad (114)$$

$$Dr_{i+\frac{1}{2}} = \frac{r_{i+\frac{1}{2}}}{(r_{i+1} - r_i) r_i \Delta r_i} \qquad (115)$$

$$Dr_{i-\frac{1}{2}} = \frac{r_{i-\frac{1}{2}}}{(r_i - r_{i-\frac{1}{2}}) r_i \Delta r_i} \qquad (116)$$

$$Dz_{j+\frac{1}{2}} = \frac{1}{(z_{j+1} - z_j)\Delta z_j} \qquad (117)$$

$$Dz_{j-\frac{1}{2}} = \frac{1}{(z_j - z_{j-1})\Delta z_j} \qquad (118)$$

$$e^{n+1}_{i,j} = e^{n}_{i,j} - \frac{\Delta t^{n+\frac{1}{2}}}{\rho^{n}_{i,j}}\left\{\frac{r_{i+\frac{1}{2}}\cdot p^{n+\frac{1}{2}}_{i+\frac{1}{2},j}\cdot v^{n+\frac{1}{2}}_{i+\frac{1}{2},j} - r_{i-\frac{1}{2}}\cdot p^{n+\frac{1}{2}}_{i-\frac{1}{2},j}\cdot v^{n+\frac{1}{2}}_{i-\frac{1}{2},j}}{r_i \Delta r_i} + \right.$$

$$\left.\frac{p^{n+\frac{1}{2}}_{i,j+\frac{1}{2}}\cdot u^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} - p^{n+\frac{1}{2}}_{i,j-\frac{1}{2}}\cdot u^{n+\frac{1}{2}}_{i,j-\frac{1}{2}}}{\Delta z_j}\right\} - \frac{\Delta t^{n+\frac{1}{2}}}{\rho^{n}_{i,j}}\left\{\frac{r_{i+\frac{1}{2}}\cdot \tau^{n}_{rr_{i+\frac{1}{2},j}}\cdot v^{n+\frac{1}{2}}_{i+\frac{1}{2},j} - r_{i-\frac{1}{2}}\cdot \tau^{n}_{rr_{i-\frac{1}{2},j}}\cdot v^{n+\frac{1}{2}}_{i-\frac{1}{2},j}}{r_i \Delta r_i}\right.$$

$$+ \frac{r_{i+\frac{1}{2}}\cdot \tau^{n}_{rz_{i+\frac{1}{2},j+\frac{1}{2}}}\cdot u^{n+\frac{1}{2}}_{i+\frac{1}{2},j} - r_{i-\frac{1}{2}}\cdot \tau^{n}_{rz_{i-\frac{1}{2},j-\frac{1}{2}}}\cdot u^{n+\frac{1}{2}}_{i-\frac{1}{2},j}}{r_i \Delta r_i}$$

$$+ \frac{\tau^{n}_{rz_{i+\frac{1}{2},j+\frac{1}{2}}}\cdot v^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} - \tau^{n}_{rz_{i-\frac{1}{2},j-\frac{1}{2}}}\cdot v^{n+\frac{1}{2}}_{i,j-\frac{1}{2}}}{\Delta z_j} + \left.\frac{\tau^{n}_{zz_{i,j+\frac{1}{2}}}\cdot u^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} - \tau^{n}_{zz_{i,j-\frac{1}{2}}}\cdot u^{n+\frac{1}{2}}_{i,j-\frac{1}{2}}}{\Delta z_j}\right\}$$

$$+ \frac{c\Delta t^{n+\frac{1}{2}}_{v}}{\rho^{n+\frac{1}{2}}_{i,j}}\left\{\left[Dr_{i+\frac{1}{2}}\cdot\frac{i^{n+\frac{1}{2}}_{i+\frac{1}{2},j}}{c_v}\cdot\lambda_{i+\frac{1}{2},j} + Dr_{i-\frac{1}{2}}\cdot\frac{i^{n+\frac{1}{2}}_{i-\frac{1}{2},j}}{c_v}\cdot\lambda_{i-\frac{1}{2},j}\right] + \left[Dz_{j+\frac{1}{2}}\cdot\frac{i^{n+\frac{1}{2}}_{i,j+\frac{1}{2}}}{c_v}\cdot\lambda_{i,j+\frac{1}{2}}\right.\right.$$

$$\left.\left. + D\cdot\frac{i^{n+\frac{1}{2}}_{i,j-\frac{1}{2}}}{c_v}\cdot\lambda_{i,j-\frac{1}{2}}\right]\right\} + \left(j^{n+\frac{1}{2}}_{z_{i,j}} E^{n+\frac{1}{2}}_{z_{i,j}} + j^{n+\frac{1}{2}}_{r_{i,j}} E^{n+\frac{1}{2}}_{r_{i,j}}\right)\frac{\Delta t^{n+\frac{1}{2}}}{\rho^{n}_{i,j}} - \left(v^{n+1}_{i,j}\cdot g_r + u^{n+1}_{i,j}\cdot g_z\right)\Delta t^{n+\frac{1}{2}} \tag{119}$$

Problems where the induced field becomes significant ($Re_m >> 1$) requires a solution to the induction equations:

$$B^{n+1}_{\theta_{i,j}} = B^{n}_{\theta_{i,j}} + \frac{\Delta t^{n+\frac{1}{2}}}{\mu_p}\left\{Dr_{i+\frac{1}{2}}\left[\frac{B^{n}_{\theta_{i,j+1}}}{\sigma^{n}_{i,j+\frac{1}{2}}} - \frac{B^{n}_{\theta_{i,j}}}{\sigma^{n}_{i,j+\frac{1}{2}}}\right] + Dr_{i-\frac{1}{2}}\left[\frac{B^{n}_{\theta_{i-1,j}}}{\sigma^{n}_{i-\frac{1}{2},j}} - \frac{B^{n}_{\theta_{i,j}}}{\sigma^{n}_{i-\frac{1}{2},j}}\right] + \right.$$

$$\left. Dz_{j+\frac{1}{2}}\left[\frac{B^{n}_{\theta_{i+1,j}}}{\sigma^{n}_{i+\frac{1}{2},j}} - \frac{B^{n}_{\theta_{i,j}}}{\sigma^{n}_{i+\frac{1}{2},j}}\right] + Dz_{j-\frac{1}{2}}\left[\frac{B^{n}_{\theta_{i,j-1}}}{\sigma^{n}_{i,j-\frac{1}{2}}} - \frac{B^{n}_{\theta_{i,j}}}{\sigma^{n}_{i,j-\frac{1}{2}}}\right]\right\} \tag{120}$$

$$B^{n+1}_{z_{i,j}} = B^{n}_{z_{i,j}} + \frac{\Delta t^{n+\frac{1}{2}}}{\mu_p}\{Dr_{i+\frac{1}{2}}[\frac{B^{n}_{z_{i,j+1}}}{\sigma^{n}_{i,j+\frac{1}{2}}} - \frac{B^{n}_{z_{i,j}}}{\sigma^{n}_{i,j+\frac{1}{2}}}] + Dr_{i-\frac{1}{2}}[\frac{B^{n}_{z_{i-1,j}}}{\sigma^{n}_{i-\frac{1}{2},j}} - \frac{B^{n}_{z_{i,j}}}{\sigma^{n}_{i-\frac{1}{2},j}}] +$$

$$Dz_{j+\frac{1}{2}}[\frac{B^{n}_{z_{i+1,j}}}{\sigma^{n}_{i+\frac{1}{2},j}} - \frac{B^{n}_{z_{i,j}}}{\sigma^{n}_{i+\frac{1}{2},j}}] + Dr_{i-\frac{1}{2}}[\frac{B^{n}_{\theta_{i,j-1}}}{\sigma^{n}_{i,j-\frac{1}{2}}} - \frac{B^{n}_{z_{i,j}}}{\sigma^{n}_{i,j-\frac{1}{2}}}]\} \quad (121)$$

$$B^{n+1}_{r_{i,j}} = B^{n}_{r_{i,j}} + \frac{\Delta t^{n+\frac{1}{2}}}{\mu_p}\{Dr_{i+\frac{1}{2}}[\frac{B^{n}_{r_{i,j+1}}}{\sigma^{n}_{i,j+\frac{1}{2}}} - \frac{B^{n}_{r_{i,j}}}{\sigma^{n}_{i,j+\frac{1}{2}}} + Dr_{i-\frac{1}{2}}[\frac{B^{n}_{r_{i-1,j}}}{\sigma^{n}_{i-\frac{1}{2},j}} - \frac{B^{n}_{r_{i,j}}}{\sigma^{n}_{i-\frac{1}{2},j}}] +$$

$$Dz_{j+\frac{1}{2}}[\frac{B^{n}_{r_{i+1,j}}}{\sigma^{n}_{i+\frac{1}{2},j}} - \frac{B^{n}_{r_{i,j}}}{\sigma^{n}_{i+\frac{1}{2},j}}] + D[\frac{B^{n}_{r_{i,j-1}}}{\sigma^{n}_{i,j-\frac{1}{2}}} - \frac{B^{n}_{r_{i,j}}}{\sigma^{n}_{i,j-\frac{1}{2}}}]\} \quad (122)$$

Problems where $Re_m << 1$, such as an MHD generator, require solution to Equation (53).

Solutions to the Elliptic PDE for Small Re_m

There are numerous numerical approaches to solving Equation (53). Three methods were considered: Alternating direction implicit (ADI), Gauss-Seidel (GS) and Successive Over-Relaxation (SOR). SOR was found to converge more rapidly in all cases and therefore was the most promising. Once Equation (53) is solved for ϕ or Ψ, the electric fields and currents are determined and the pondermotive force ($\bar{j}x\bar{B}$) and electric energy ($\bar{j}\cdot\bar{E}$) become known quantities in the momentum and energy equations. Computation of a new fluid dynamics state will influence the behavior of currents which result in a "coupled solution" necessitating solving Equation (53) frequently if currents are strongly dependent on the flow field or infrequently if the currents are weakly dependent on the flow field.

A discussion of the solution of Equation (53) by ADI, GS or SOR follows. ADI has already been employed to solve the thermal magnetic diffusion described by Equations (49) through (51) and (36).

In the MHD generator under consideration, the magnetic field is time independent, thus satisfying Equations (54) and (55) identically. A time dependent (induced) magnetic field which is frozen to the fluid and/or diffusing into the neighboring medium would create a time dependent potential (or stream current) term in Equation (53). In this case, it would be necessary to solve the magnetic induction Equations (49) through (51).

Considering the ADI method, the numerical solution to Equation (53) was performed implicitly by "sweeping" along the axial and radial (or Cartesian) coordinates and summing the contributions of gradients in both directions. Expressing the derivatives in terms of finite difference expressions, summing, and rearranging, a series of simultaneous algebraic equations results. The coefficient matrix of the dependent variable representing these algebraic equations is in tridiagonal form and is expeditiously inverted without the need for iteration. The matrix is decomposed into upper and lower matrices and solved exactly equation by equation. The (zeroth) first and second derivatives (in the z-direction) are cast in the following finite difference expressions:*

$$\frac{\delta}{\delta z}(\phi_{i,j}) = \phi_{i,j+\frac{1}{2}}[\frac{1}{\Delta z_j}]-\phi_{i,j-\frac{1}{2}}[\frac{1}{\Delta z_j}] \qquad (123)$$

*ψ replaces ϕ if Equation (66) is to be solved instead of (63).

$$\frac{\delta}{\delta z}\left[\frac{\delta}{\delta z}(\phi_{i,j})\right] = \frac{1}{\Delta z_j}\left[\left(\frac{\phi_{i,j+\frac{1}{2}}-\phi_{i,j}}{z_{j+1}-z_j}\right)-\left(\frac{\phi_{i,j}-\phi_{i,j-\frac{1}{2}}}{z_j-z_{j-1}}\right)\right] \tag{124}$$

$$\frac{\delta}{\delta z}[\ln(\sigma_\dagger)] = \frac{1}{\sigma_{\dagger_{i,j}}}\frac{1}{\Delta z_j}\left(\sigma_{\dagger_{i,j+\frac{1}{2}}}-\sigma_{\dagger_{i,j-\frac{1}{2}}}\right) \tag{125}$$

$$\frac{\delta}{\delta z}(\beta) = \frac{1}{\Delta z_j}\left(\beta_{i,j+\frac{1}{2}}-\beta_{i,j-\frac{1}{2}}\right) \tag{126}$$

$$\frac{\delta}{\delta z}(vB+\beta uB) = \frac{1}{\Delta z_j}\left[\left(v_{i,j+\frac{1}{2}}\cdot B_{i,j+\frac{1}{2}}+\beta_{i,j+\frac{1}{2}}\cdot u_{i,j+\frac{1}{2}}\cdot B_{i,j+\frac{1}{2}}\right)-\right.$$

$$\left.\left(v_{i,j-\frac{1}{2}}\cdot B_{i,j-\frac{1}{2}}+\beta_{i,j-\frac{1}{2}}\cdot v_{i,j-\frac{1}{2}}\cdot B_{i,j-\frac{1}{2}}\right)\right] \tag{127}$$

Equation (53) becomes in finite difference form:

$$A_j\phi_{i,j+\frac{1}{2}}+B_j\phi_{i,j}+C_j\phi_{i,j-\frac{1}{2}} = D_j \tag{128}$$

for the i,jth cell. Sweeping across the jth row, j simultaneous equations result. In relaxing to the steady state solution: the left-hand side of Equation (53) was set = to(ϕ (new) - ϕ (old))/Δt and iterations proceeded until ϕ (new)= ϕ (old) or the right-hand side of Equation (53) was equal to zero.

$$A_3\phi_4+B_3\phi_3+C_3\phi_2 = D_3 \tag{129}$$

$$A_2\phi_3+B_2\phi_2+\phi_1 = D_2 \tag{130}$$

$$A_1\phi_2+B_1\phi_1 = D_1 \tag{131}$$

where the coefficients A(j), B(j), C(j) and D(j) are:

$$A_j = \frac{1}{(z_{j+1}-z_j)\Delta z_j}+\frac{1}{\Delta z_j}\left[\frac{1}{\sigma_{\dagger_{i,j}}}\left(\frac{\sigma_{\dagger_{i,j+\frac{1}{2}}}-\sigma_{\dagger_{i,j-\frac{1}{2}}}}{\Delta z_j}\right)+\frac{\beta_{i,j}}{\sigma_{\dagger_{i,j}}}\right.$$

$$\left.\left\{\left(\frac{\sigma_{\dagger_{i+\frac{1}{2},j}}-\sigma_{\dagger_{i-\frac{1}{2},j}}}{\Delta r_i}\right)+\left(\frac{\beta_{j+\frac{1}{2},j}-\beta_{i-\frac{1}{2},j}}{\Delta r_i}\right)\right\}\right] \tag{132}$$

$$B_j = \left[-\frac{1}{(z_{j+1}-z_j)\Delta z_j} - \frac{1}{(z_{j-1}-z_j)\Delta z_j}\right]\frac{1}{\Delta t} \tag{133}$$

$$C_j = \frac{1}{(z_{j-1}-z_j)\Delta z_j} - \frac{1}{\Delta z_j}\left[\frac{1}{\sigma_{\dagger_{i,j}}}\left(\frac{\sigma_{\dagger_{i,j+\frac{1}{2}}} - \sigma_{\dagger_{i,j-\frac{1}{2}}}}{\Delta z_j}\right) + \frac{\beta_{i,j}}{\sigma_{\dagger_{i,j}}}\right.$$

$$\left.\left\{\left(\frac{\sigma_{\dagger_{i+\frac{1}{2},j}} - \sigma_{\dagger_{i-\frac{1}{2},j}}}{\Delta r_i}\right) + \left(\frac{\beta_{i+\frac{1}{2},j} - \beta_{i-\frac{1}{2},j}}{\Delta r_i}\right)\right\}\right] \tag{134}$$

$$D_j = -\left[v_{i,j}\cdot B_{i,j} + \beta_{i,j}\cdot u_{i,j}\cdot B_{i,j}\right]\frac{1}{\sigma_{\dagger_{i,j}}}\frac{1}{\Delta z_j}\left(\sigma_{\dagger_{i,j+\frac{1}{2}}} - \sigma_{\dagger_{i,j-\frac{1}{2}}}\right) \tag{135}$$

Similar relations are developed for the column sweep. The solution to ϕ occurs when the potential has relaxed to its steady state value and no discernible change in ϕ occurs in ensuing iterations.

The G-S technique relaxes to a numerical solution by use of the algorithm:

$$\phi^{n+1}_{i,j} = \phi^{n}_{i,j} + \left(-D_i - D_j + A_i\phi^{n}_{i+1,j} + A_j\phi^{n}_{i,j+1} + C_i\phi^{n}_{i-1,j} + C_j\phi^{n}_{i,j-1}\right)/(B_i + B_j) \tag{136}$$

or

$$\Psi^{n+1}_{i,j} = \Psi^{n}_{i,j} + \left(-D_i - D_j + A_i\Psi_{i+1,j} + A_j\Psi^{n}_{i,j+1} + C_i\Psi^{n}_{i-1,j} + C_j\Psi^{n}_{i,j-1}\right)/B_i + B_j) \tag{137}$$

where axial coefficients A_j, B_j, C_j and D_j are defined by Eqns. (132)-(135) and radial coefficients A_i, B_i, C_i and D_i are derived in the same manner.

SOR employs the GS method, with acceleration to convergence achieved by employing the modified algorithm:

$$\phi_{i,j}^{n+1} = \omega \phi_{i,j}^{n} + (1-\omega)\phi_{i,j}^{n+1} \tag{138}$$

or

$$\Psi_{i,j}^{n+1} = \omega \Psi_{i,j}^{n} + (1-\omega)\Psi_{i,j}^{n} \tag{139}$$

where $\omega = 1.75$ ($\omega = 0$ yields the g-s method).

Oliver (58) discusses the influence of electromagnetic properties on the rate of convergence and suggests, in some cases, under-relaxation ($\omega = 0.2$). SOR was found to converge more rapidly than GS or ADI and thus was the method employed to solve Eqn (53).

Results of a variety of problems are presented in section (3.5).

ϕ or Ψ Boundary Conditions

The electrical boundary conditions on the electrodes as derived in Appendix (A.2) are:

$$\frac{\delta}{\delta r}(\Psi) = \beta \frac{\delta}{\delta z}(\Psi); \quad \frac{\delta}{\delta z}(\phi) = 0: \text{ conductor} \tag{140}$$

$$\frac{\delta}{\delta r}(\phi) = -\beta \frac{\delta}{\delta z}(\phi); \quad \frac{\delta}{\delta z}(\Psi) = 0: \text{ insulator} \tag{141}$$

Equation (53) is completely described by the boundary conditions. In addition, the electrical relation between the generator (internal circuit) and external circuit must be specified in order to provide a complete set of boundary conditions necessary for solving the elliptic partial differential equation. The particular generator, e.g., Faraday, Hall, Diagonal,* etc., determines the nature of the boundary conditions employed and further furnishes impetus for employing either ϕ or Ψ, in order to determine the electric field and currents.

*The primary difference between the Faraday, Hall and Diagonal generator is the alignment of the electrode-pairs in the MHD channel.

The difficult boundary condition to specify occurs at infinity, but for the Faraday generator, the stream current function is used since at

$$z = \infty, \ \Psi = \Psi_{\infty} = 0 \tag{142}$$

and is constant up to the first electrode. For the Hall generator, use is made of the potential because at

$$z = \infty, \ \phi = \phi_{\infty} = A \tag{143}$$

is known, and is constant up to the first insulator.

Appendix (A.2) contains an in-depth discussion and derivation of the electrical boundary conditions in both the electric potential and stream current function.

Phase II (Eulerian Frame of Reference)

Once the new velocities are known, the convective terms in the differential equations can be computed by transporting mass from a cell

$$i^{\rightarrow} = i(v^{n+1}_{i+\frac{1}{2},j}>1), \ i^{\leftarrow} = i+1(v^{n+1}_{i+\frac{1}{2},j}<1) \tag{144}$$

$$j^{\uparrow} = j(u^{n+1}_{i,j+\frac{1}{2}}>1), \ j^{\downarrow} = j+1(u^{n+1}_{i,j+\frac{1}{2}}<1) \tag{145}$$

$$\rho^{n+1}_{i+\frac{1}{2},j} = \rho^{n}_{i^{\leftarrow},j}\left\{1-\frac{\Delta t^{n+1}}{r_{i+\frac{1}{2}}}\cdot\frac{r_{i+1}v^{n+1}_{i+1,j}-r_i v^{n+1}_{i,j}}{r_{i+1}-r_i}\right\} \tag{146}$$

$$\rho^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} = \rho^{n}_{i,j^{\downarrow}}\left\{1-\Delta t^{n+1}\cdot\frac{u^{n+1}_{i,j+1}-u^{n+1}_{i,j}}{z_{j+1}-z_j}\right\} \tag{147}$$

to its neighbors. In Equations (146) and (147), the densities are updated, based on the velocities. The mass fluxes are computed in Equations (148) and (149) and based on these values, the momentum, energy and magnetic transport values are computed in Equations (150) through (161).

$$F_{m_{i+\frac{1}{2}}} = v^{n+1}_{i+\frac{1}{2},j} \cdot \rho^{n+1}_{i+\frac{1}{2},j} \cdot 2 \cdot \pi \cdot r_{i+\frac{1}{2}} \left(1 + \frac{1}{2} \cdot v^{n+1}_{i+\frac{1}{2},j} \Delta t^{n+1}\right) \cdot \Delta z_j \cdot \Delta t^{n+1} \tag{148}$$

$$F^{n+1}_{m_{j+\frac{1}{2}}} = u^{n+1}_{i,j+\frac{1}{2}} \cdot \rho^{n+1}_{i,j+\frac{1}{2}} \cdot 2 \cdot \pi \cdot r_i \left(1 + \frac{1}{2} \cdot u^{n+1}_{i,j+\frac{1}{2}} \Delta t^{n+1}\right) \cdot \Delta r_i \cdot \Delta t^{n+1} \tag{149}$$

$$F^{n+1}_{u_{i+\frac{1}{2}}} = F^{n+1}_{m_{i+\frac{1}{2}}} \cdot u^{n+1}_{i',j} \tag{150}$$

$$F^{n+1}_{v_{i+\frac{1}{2}}} = F^{n+1}_{m_{i+\frac{1}{2}}} \cdot v^{n+1}_{i',j} \tag{151}$$

$$F^{n+1}_{u_{j+\frac{1}{2}}} = F^{n+1}_{m_{j+\frac{1}{2}}} \cdot u^{n+1}_{i,j'} \tag{152}$$

$$F^{n+1}_{v_{j+\frac{1}{2}}} = F^{n+1}_{m_{j+\frac{1}{2}}} \cdot v^{n+1}_{i,j'} \tag{153}$$

$$F^{n+1}_{e_{i+\frac{1}{2}}} = F^{n+1}_{m_{i+\frac{1}{2}}} \cdot e^{n+1}_{i',j} \tag{154}$$

$$F^{n+1}_{e_{j+\frac{1}{2}}} = F^{n+1}_{m_{j+\frac{1}{2}}} \cdot e^{n+1}_{i,j'} \tag{155}$$

$$m^{n+1}_{r_{i+\frac{1}{2}}} = \frac{v^{n+1}_{i,j+\frac{1}{2}} \cdot B^{n+1}_{z_{i,j+\frac{1}{2}}} \cdot \Delta t^{n+1}}{z_{j+1} - z_j} \tag{156}$$

$$m^{n+1}_{r_{j+\frac{1}{2}}} = \frac{u^{n+1}_{i,j+\frac{1}{2}} \cdot B^{n+1}_{r_{i,j'}} \cdot \Delta t^{n+1}}{z_{j+1} - z_j} \tag{157}$$

$$m^{n+1}_{z_{i+\frac{1}{2}}} = \frac{v^{n+1}_{i+\frac{1}{2},j} \cdot B^{n+1}_{z_{i',j}} \cdot \Delta t^{n+1}}{r_{i+1} - r_i} \tag{158}$$

$$m^{n+1}_{z_{j+\frac{1}{2}}} = \frac{u^{n+1}_{i+\frac{1}{2},j} \cdot B^{n+1}_{r_{i+\frac{1}{2},j}} \cdot \Delta t^{n+1}}{r_{i+1} - r_i} \tag{159}$$

$$m_{\theta_{i+\frac{1}{2}}}^{n+1} = \frac{v_{i+\frac{1}{2},j}^{n+1} \cdot B_{\theta_{i,j}}^{n+1} \cdot \Delta t^{n+1}}{r_{i+1} - r_i} \tag{160}$$

$$m_{\theta_{j+\frac{1}{2}}}^{n+1} = \frac{u_{i,j+\frac{1}{2}}^{n+1} \cdot B_{\theta_{i,j}}^{n+1} \cdot \Delta t^{n+1}}{z_{j+1} - z_j} \tag{161}$$

Finally, the new mass, density, velocities, energy and magnetic fields are computed at time (n+1) at the center of each cell based on the convection terms in phase II and force terms in phase I.

$$M_{i,j}^{n+1} = M_{i,j}^{n} + F_{m_{i-\frac{1}{2}}}^{n+1} + F_{m_{j-\frac{1}{2}}}^{n+1} - F_{m_{i+\frac{1}{2}}}^{n+1} - F_{m_{j+\frac{1}{2}}}^{n+1} \tag{162}$$

$$\rho_{i,j}^{n+1} = \frac{M_{i,j}^{n+1}}{\pi(r_{i+\frac{1}{2}}^2 - r_{i-\frac{1}{2}}^2)\Delta z_j} \tag{163}$$

$$u_{i,j}^{n+1} = \frac{u_{i,j}^{n+1} \cdot M_{i,j}^{n} + F_{u_{i-\frac{1}{2}}}^{n+1} + F_{u_{j-\frac{1}{2}}}^{n+1} - F_{u_{i+\frac{1}{2}}}^{n+1} - F_{u_{j+\frac{1}{2}}}^{n+1}}{M_{i,j}^{n+1}} \tag{164}$$

$$v_{i,j}^{n+1} = \frac{v_{i,j}^{n+1} \cdot M_{i,j}^{n} + F_{v_{i-\frac{1}{2}}}^{n+1} + F_{v_{j-\frac{1}{2}}}^{n+1} - F_{v_{i+\frac{1}{2}}}^{n+1} - F_{v_{j+\frac{1}{2}}}^{n+1}}{M_{i,j}^{n+1}} \tag{165}$$

$$e_{i,j}^{n+1} = \frac{e_{i,j}^{n+1} \cdot M_{i,j}^{n} + F_{e_{i-\frac{1}{2}}}^{n+1} + F_{e_{j-\frac{1}{2}}}^{n+1} - F_{e_{i+\frac{1}{2}}}^{n+1} - F_{e_{j+\frac{1}{2}}}^{n+1}}{M_{i,j}^{n+1}} \tag{166}$$

$$B_{r_{i,j}}^{n+1} = B_{r_{i,j}}^{n+1} + m_{r_{j-\frac{1}{2}}}^{n+1} - m_{r_{i-\frac{1}{2}}}^{n+1} - m_{r_{i+\frac{1}{2}}}^{n+1} + m_{r_{j+\frac{1}{2}}}^{n+1} \tag{167}$$

$$B_{z_{i,j}}^{n+1} = B_{z_{i,j}}^{n+1} + m_{z_{j-\frac{1}{2}}}^{n+1} - m_{z_{i-\frac{1}{2}}}^{n+1} - m_{z_{j+\frac{1}{2}}}^{n+1} + m_{z_{j+\frac{1}{2}}}^{n+1} \tag{168}$$

$$B_{\theta_{i,j}}^{n+1} = B_{\theta_{i,j}}^{n+1} + m_{\theta_{j-\frac{1}{2}}}^{n+1} + m_{\theta_{i-\frac{1}{2}}}^{n+1} - m_{\theta_{i+\frac{1}{2}}}^{n+1} - m_{\theta_{j+\frac{1}{2}}}^{n+1} \tag{169}$$

III. DISCUSSION AND APPLICATION OF PHENOMENA INDUCED BY HYDRODYNAMIC, VISCOUS OR ELECTROMAGNETIC FORCES

The effectiveness of a numerical procedure is measured by its ability to reproduce the results of experiments or classical analytical solutions. In this section, there are a variety of problems solved numerically which illustrate some fundamental physical process influencing the behavior of an electrically conducting fluid. In each case, the numerical results were compared with experimental data or a closed form analytic solution. Once established that the technique can solve the classic problems, the more challenging applications are considered.

Problems are categorized into five areas: shocks, boundary layers, compressible flow, diffusion and Emf forces. Each subsection details the make-up and solution of the particular problem being investigated.

3.1 Shocks

Shocks were examined in a variety of problems: supersonic flow over a sharp-nosed projectile, shock tube flow with and without magnetic fields, regular-irregular (Mach) reflection generated by flow over a wedge, supersonic flow over a semi-infinite cylinder and hypersonic flow over a blunt-nose re-entry vehicle.

A test was run and compared with HULL to check out the hydrodynamic logic. A shock tube containing a diaphragm separating a low pressure region (40 atm) from a high pressure region (4,000 atm) was modeled.

After bursting of the diaphragm, calculations proceeded employing both programs and the results were identical in both cases. Referring to Figure (9), a shock was initiated from a pressure ratio of 100 generating a particle velocity of $1.5 \cdot 10^6$ cm/sec. Under the severe pressure gradient introduced by this test, no evidence of any numerical instability occurred. This shock tube problem is explored in greater depth later in this section.

A problem of interest to the aerodynamicist is shock attachment or detachment over a sharp-nosed projectile. Considering projectiles of nose angles of 20°, 35° and 45° in a Mach three airstream, attached and detached shocks were generated. Further, by changing the free stream Mach number, the shock can be re-attached. Figure (10) shows an attached shock at Mach three and angle 20°. Increasing the nose angle to 35°, the shock begins to detach. At 45°, the shock is further displaced from the body. Decreasing the Mach number to two (30°), the shock originally attached, detaches, as seen in Figure (11). Results compare favorably with theory (89), which predicts shock angles of 37° and 62° for nose angles of 20° and 35° as compared with shock angles of 39° and 58° developed numerically.

Referring to Figure (12), further analysis of the shock system reveals that initially a shock (compression) occurs followed by an expansion about the wedge turning point. For a fixed inlet Mach number, the angle of the projectile nose determines the location and direction of the oblique shock. As the projectile nose exceeds a critical angle, a normal shock develops in the vicinity of the projectile nose and detaches a distance depending on the inlet Mach number and nose angle.

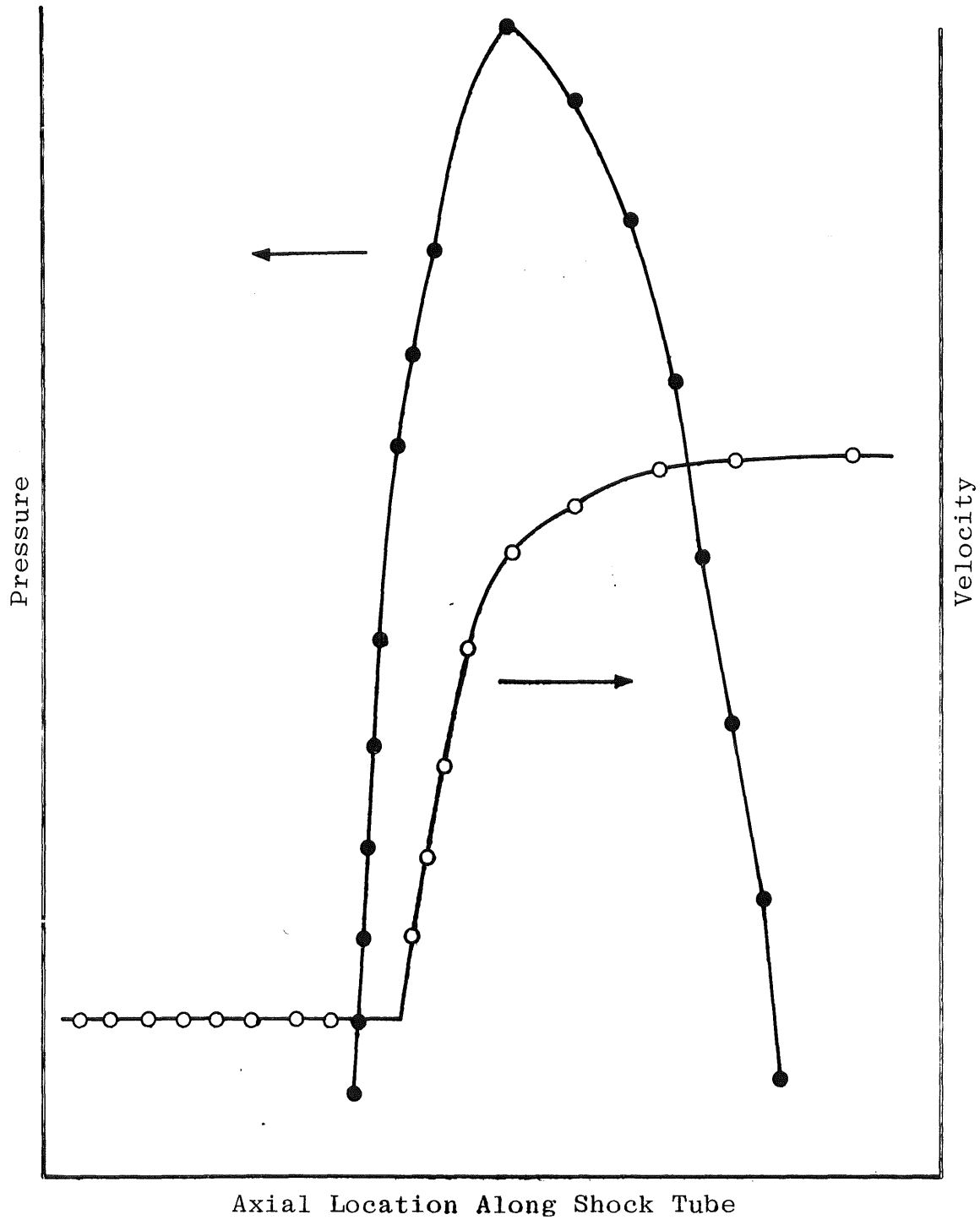
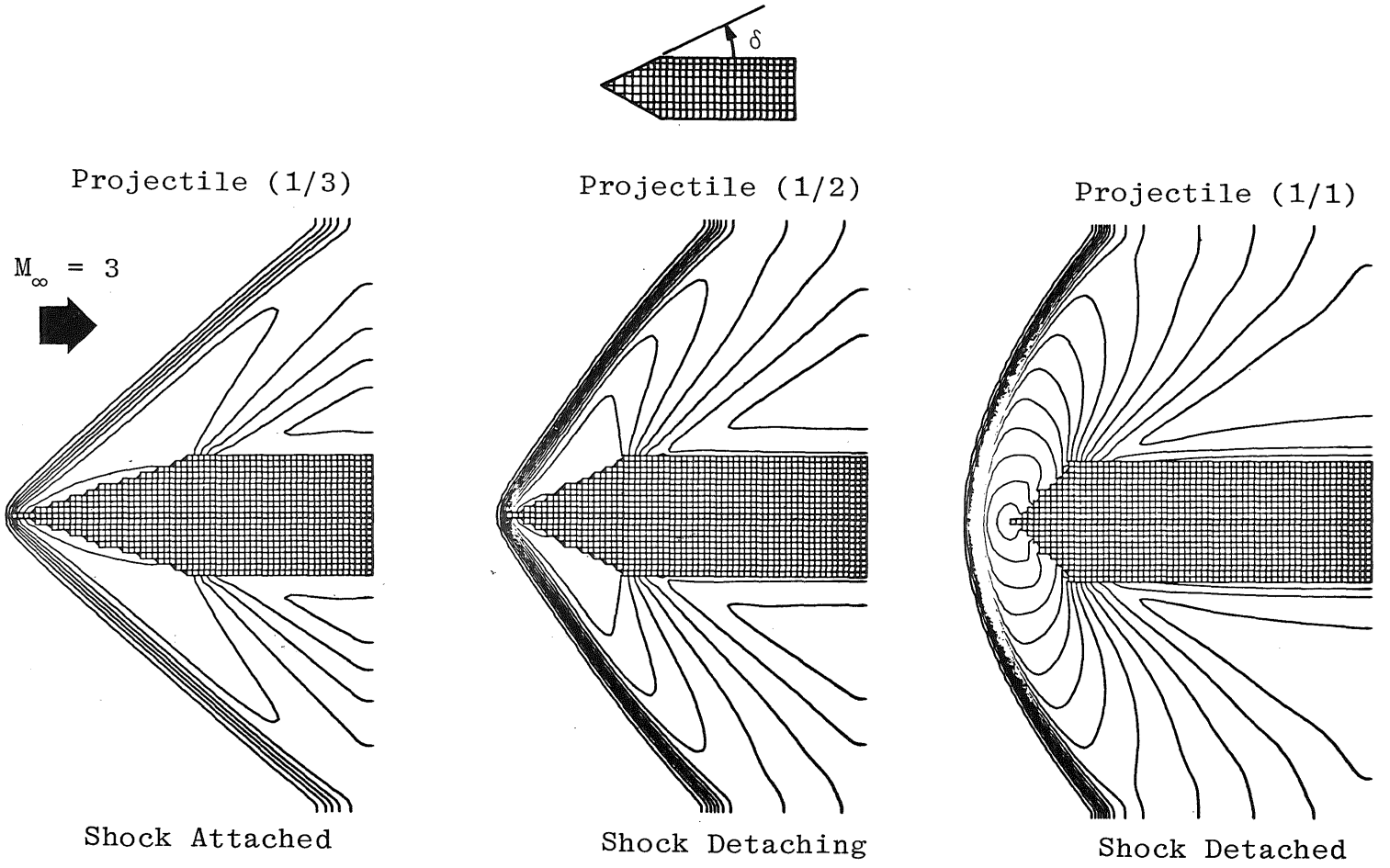


Fig. 9 Comparison of Computer Programs for Shock Tube Test Case



a. $\delta = \tan^{-1}(1/3)$ b. $\delta = \tan^{-1}(1/2)$ c. $\delta = \tan^{-1}(1/1)$

Fig. 10 Sharp-Nosed Projectiles of Angles 20^{o}, 35^{o}, and 45^{o}

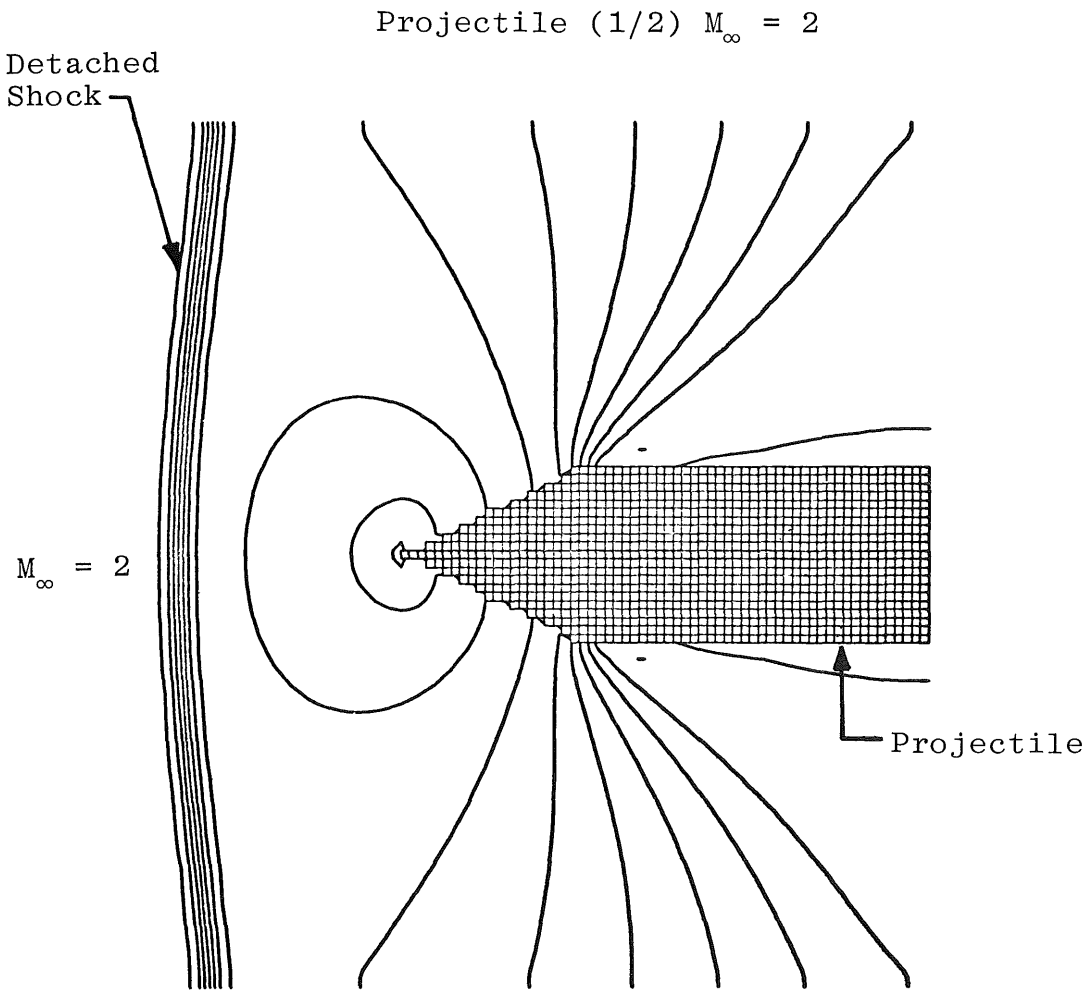


Fig. 11 Detached Shock for a 30° Wedge

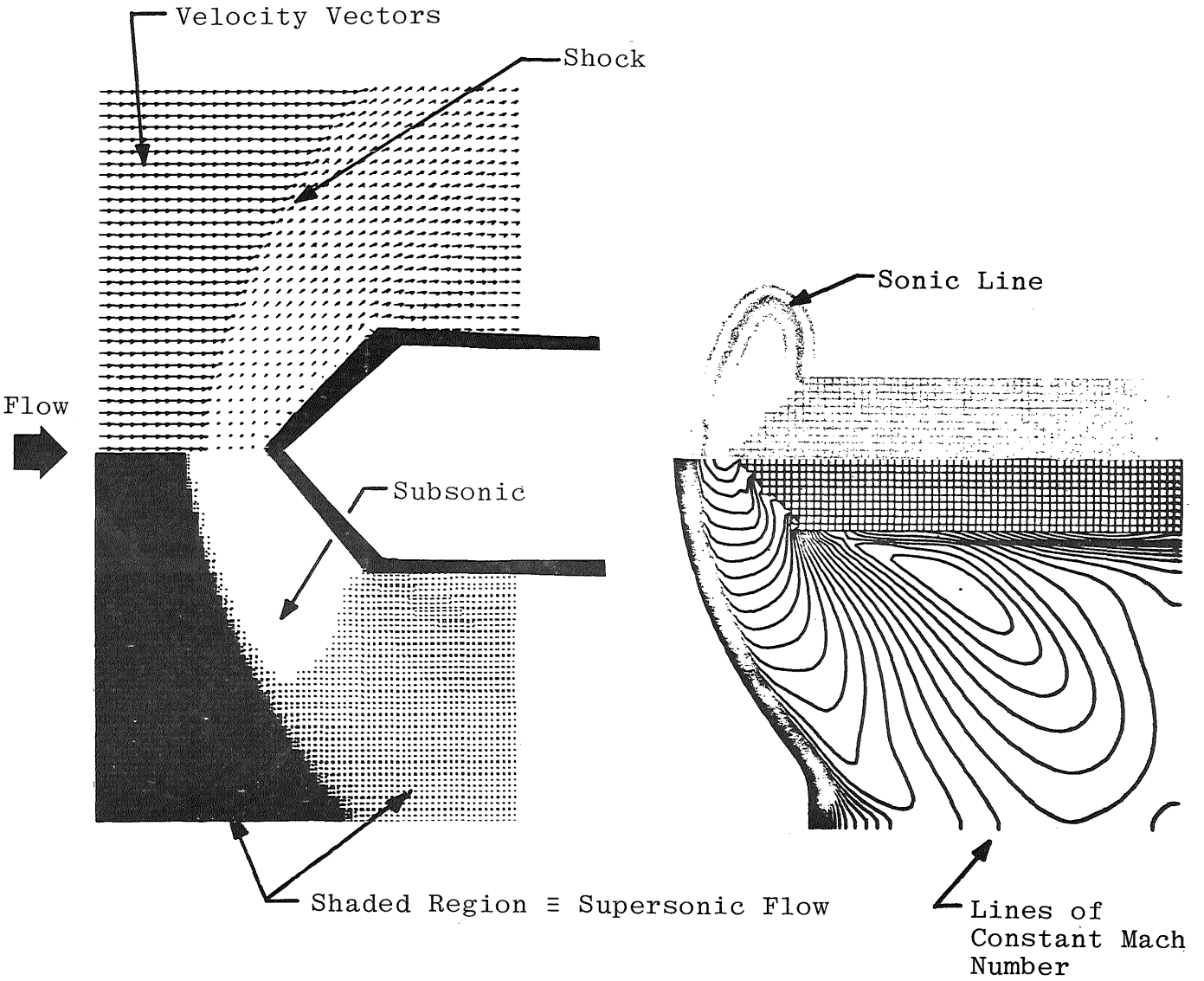


Fig. 12 Sonic Line for a 48° Wedge

The normal or strongly oblique detached shock compresses the flow from supersonic to subsonic conditions. However as the flow expands, a sonic condition (sonic line in Figure (12)) is reached, wherein the flow once again becomes supersonic. Although this problem presents no special challenge to a transient explicit finite difference procedure, other techniques, such as the method of characteristics, etc., cannot treat both the subsonic and supersonic regimes. Figure (13) illustrates a detached shock for a 45° wedge and Figure (14) depicts the transient formation of an attached shock over a 20° wedge.

In the early 1960's (65), studies were performed to determine the feasibility of employing magnetic fields to control highly ionized, conducting external flow fields. Applying a magnetic field of 0-1 Tesla to the projectile (20°) already computed, and assuming infinite conductivity, the shock was made to detach from the body. Initially, a magnetic field of 0.5 Tesla distorted the shock (Figure (15)) and increasing the magnetic field to 0.75 Tesla caused detachment. A magnetic field of 1 Tesla further detaches the shock. Vehicle weight limitations prohibited use of onboard magnets to actually attain this objective.

Shock Tube

Employing a less severe pressure gradient, numerical results were compared with shock tube theory and the Rankine-Hugoniot equations. Referring to Figure (16a) and Equations (170) to (172), a pressure

$$u_p = u_1 - u_2 = C_s\left(1-\frac{u_2}{u_1}\right) \tag{170}$$

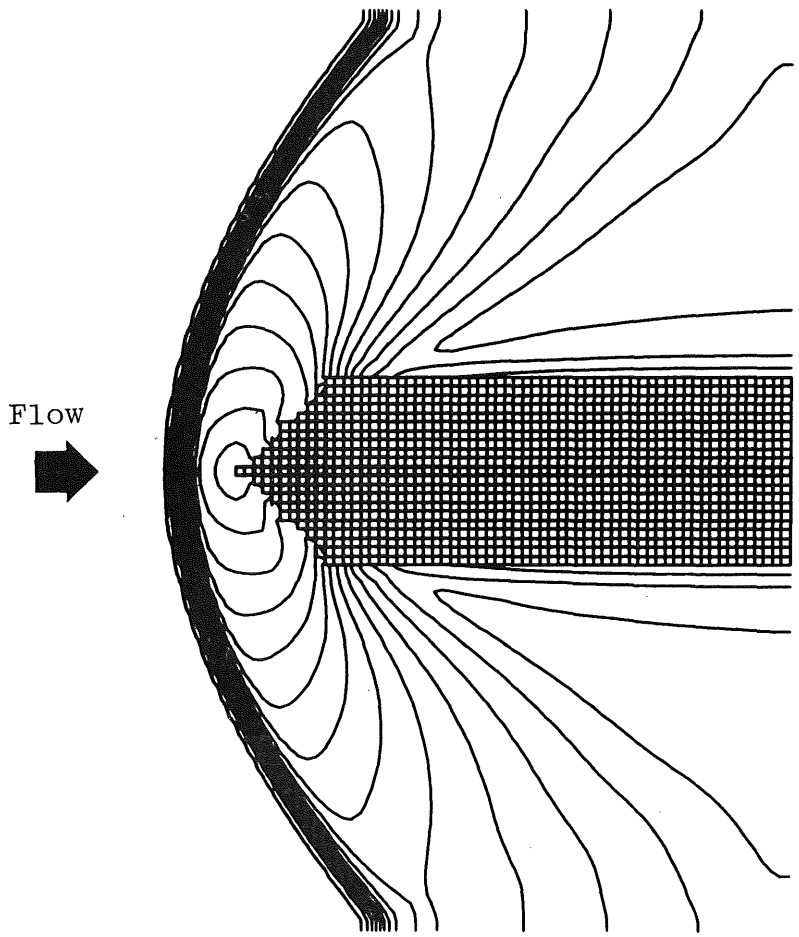
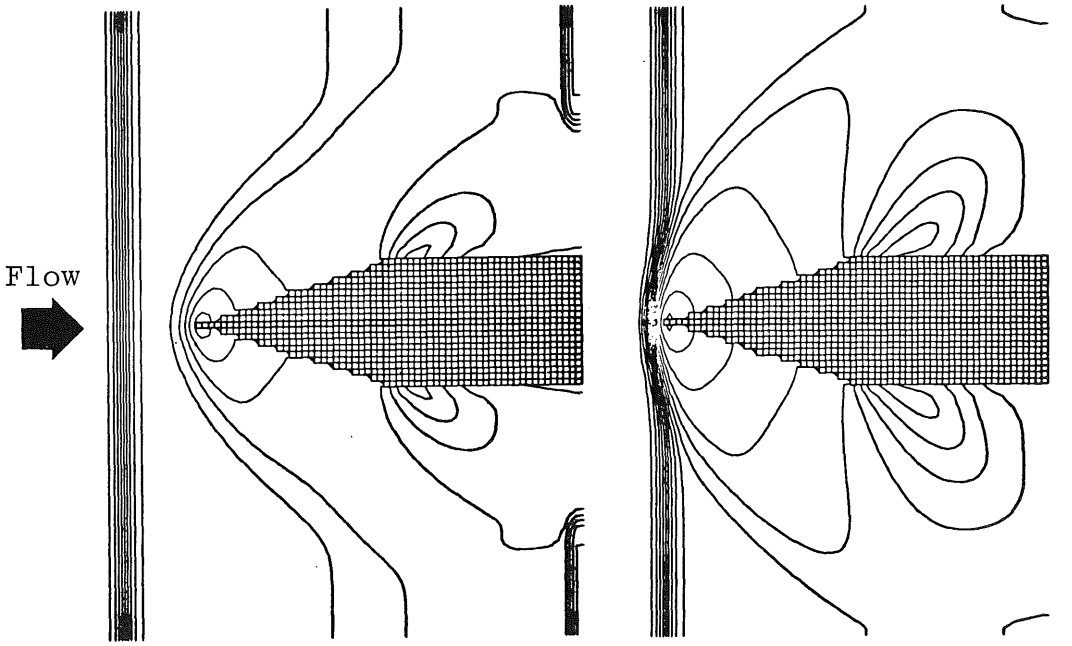
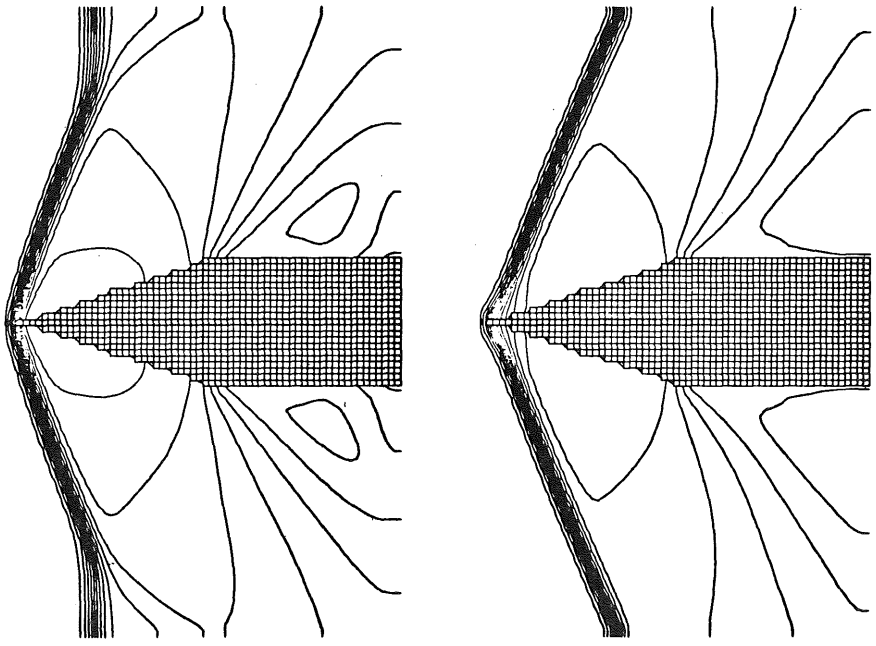


Fig. 13 Detached Shock for a 45^{O}Wedge



a. Time = t_1

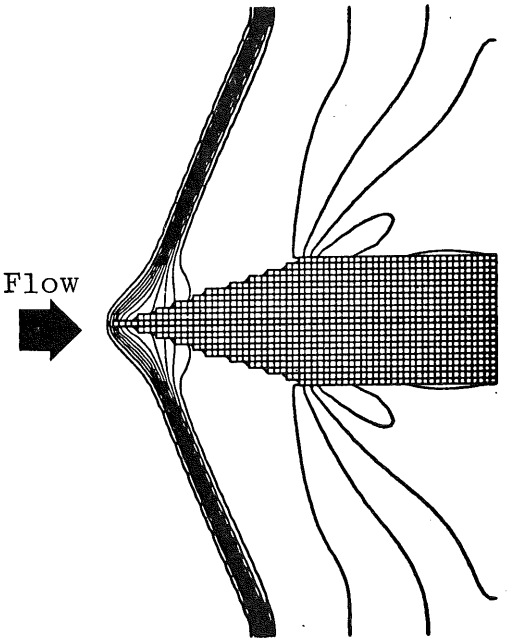
b. Time = t_2



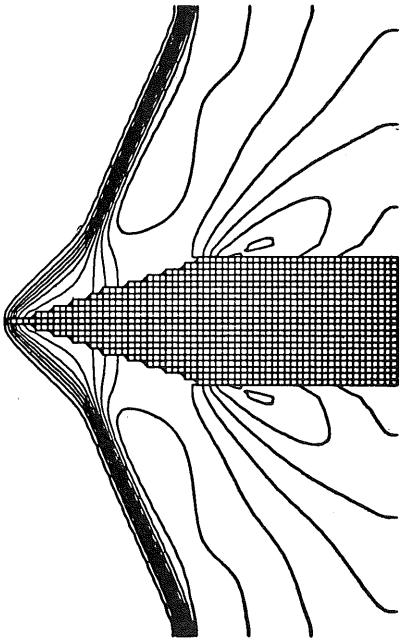
c. Time = t_3

d. Time = t_4

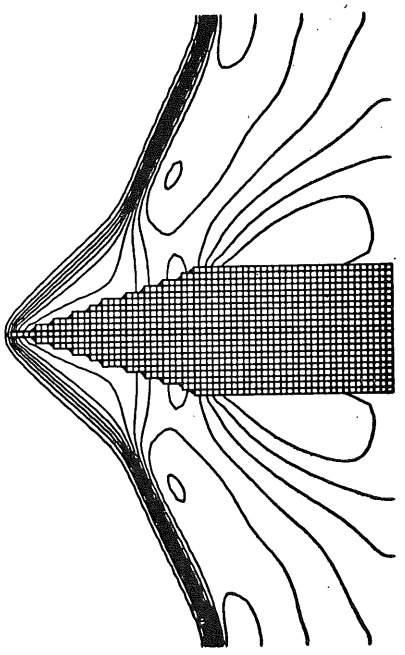
Fig. 14 Transient Shock Formation



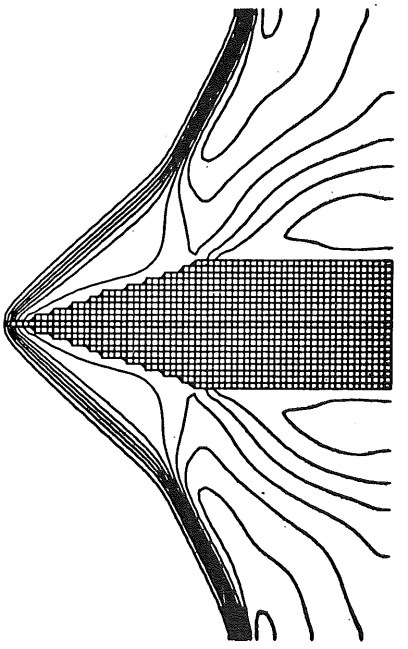
e. Time = t_5



f. Time = t_6

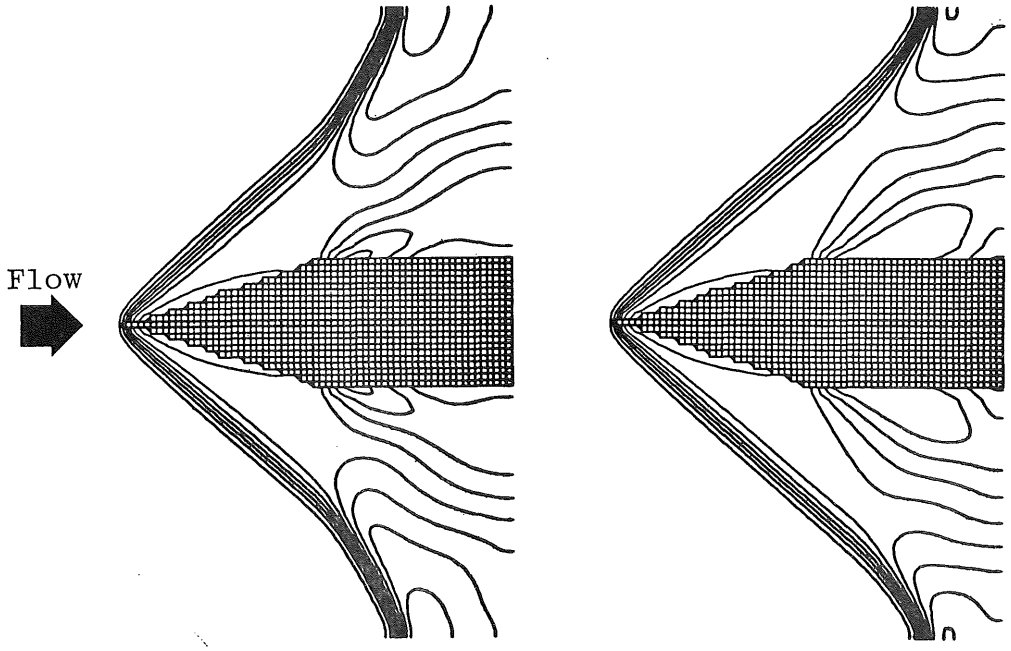


g. Time = t_7



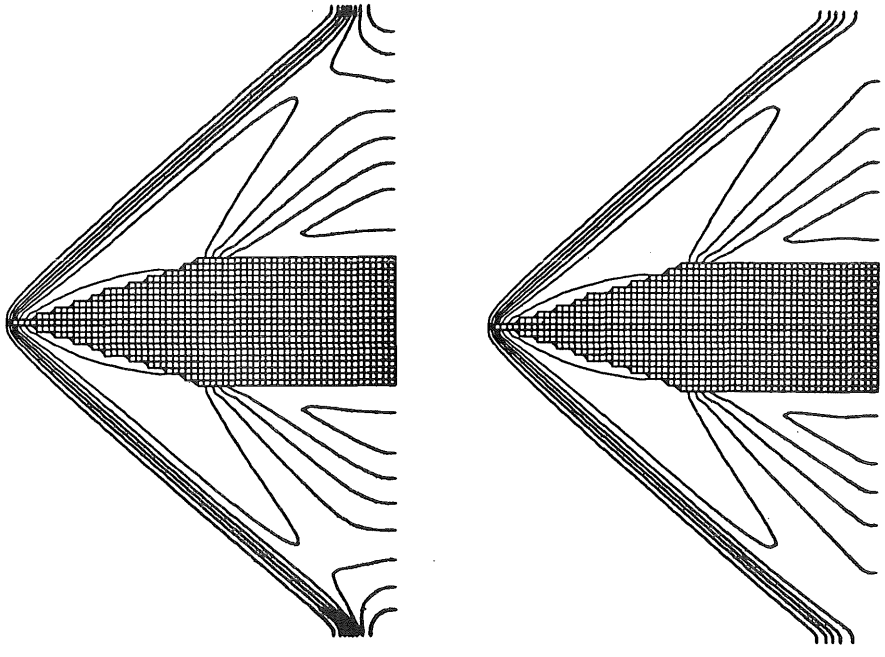
h. Time = t_8

Fig. 14 (Continued)



i. Time = t_9

j. Time = t_{10}



k. Time = t_{11}

l. Time = t_{12}

Fig. 14 (Continued)

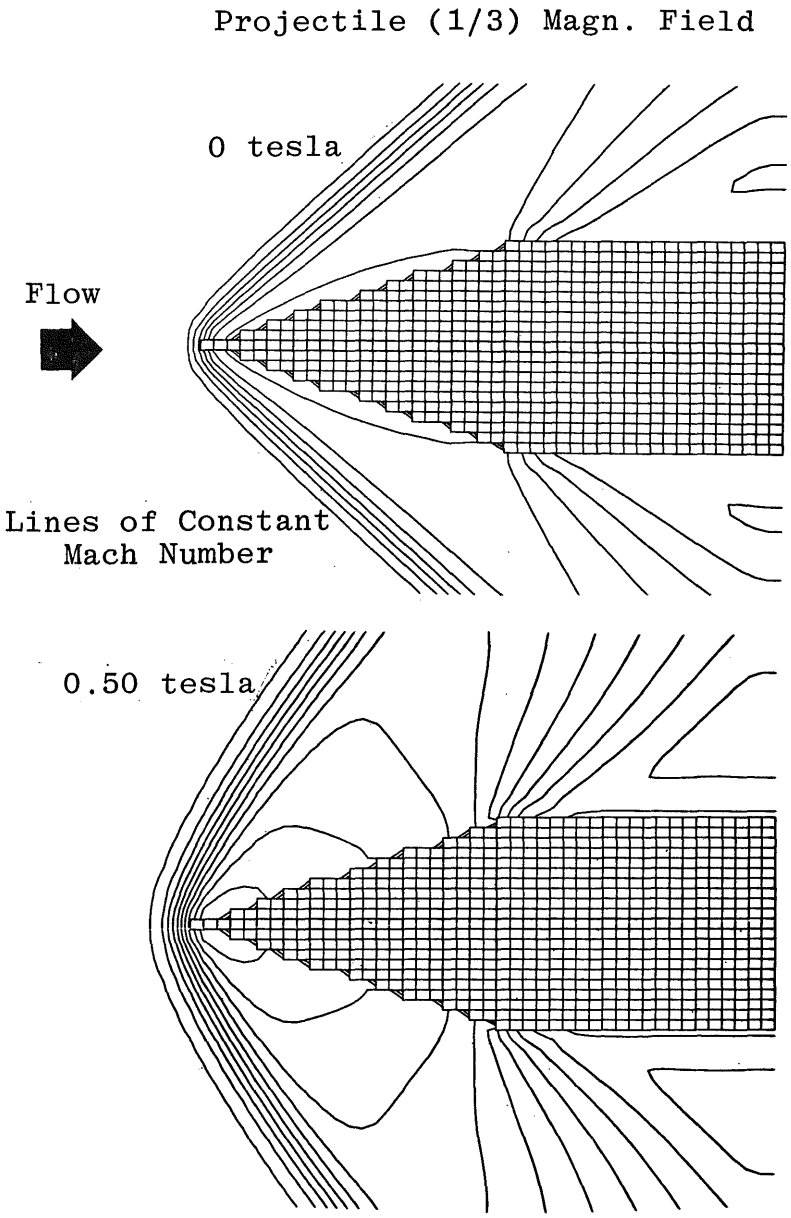


Fig. 15 Shock Detachment Induced by a Transverse Magnetic Field

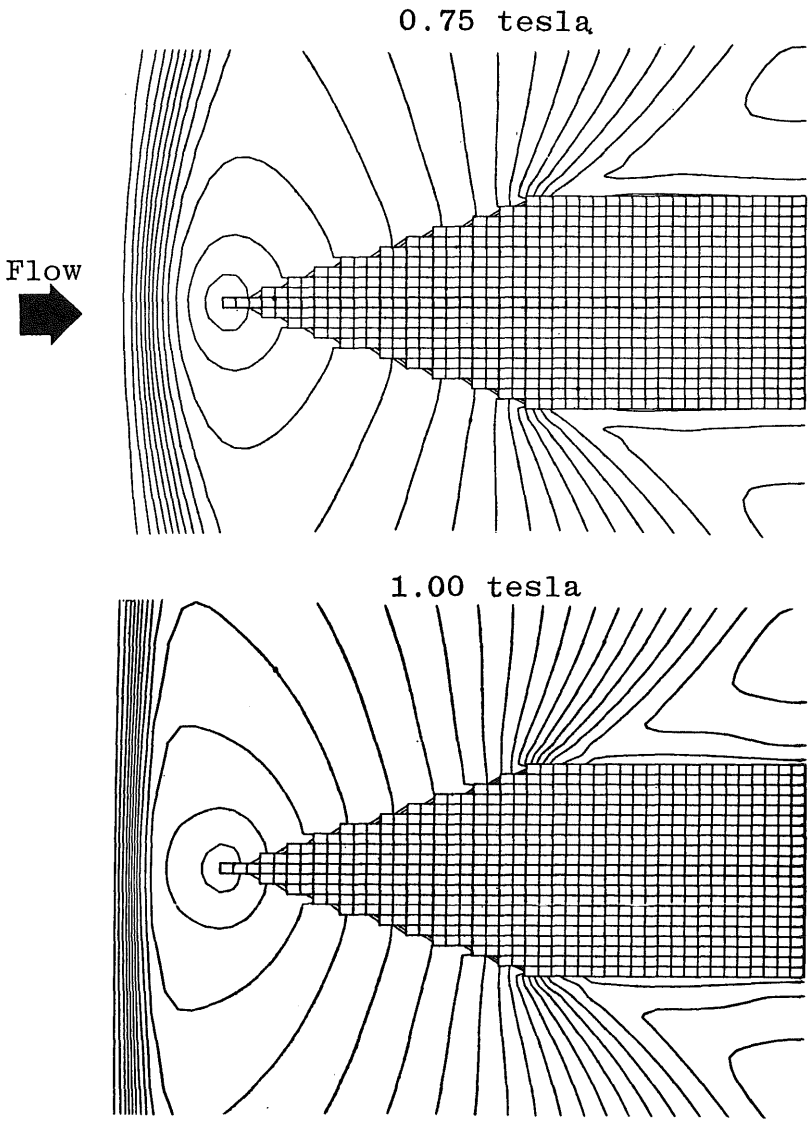


Fig. 15 (Continued)

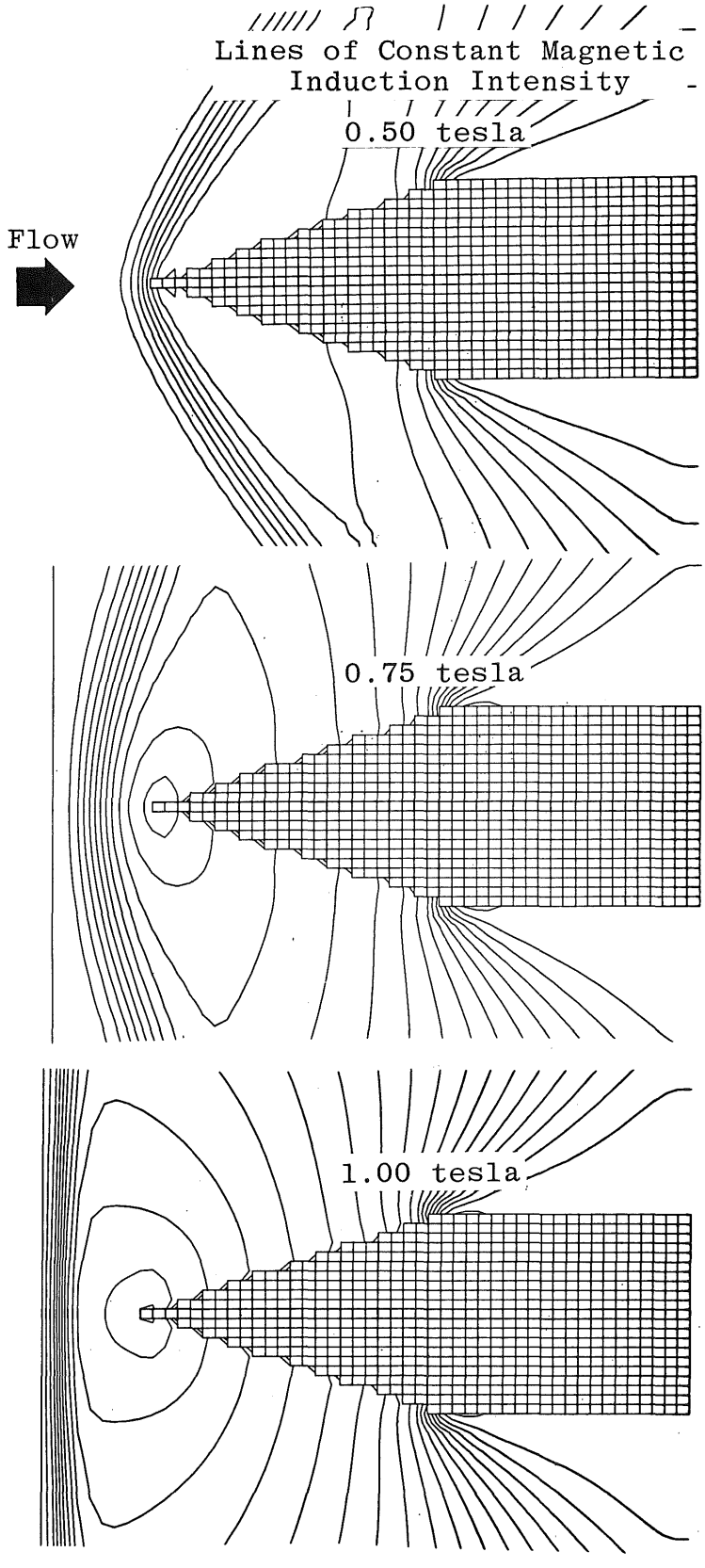


Fig. 15 (Continued)

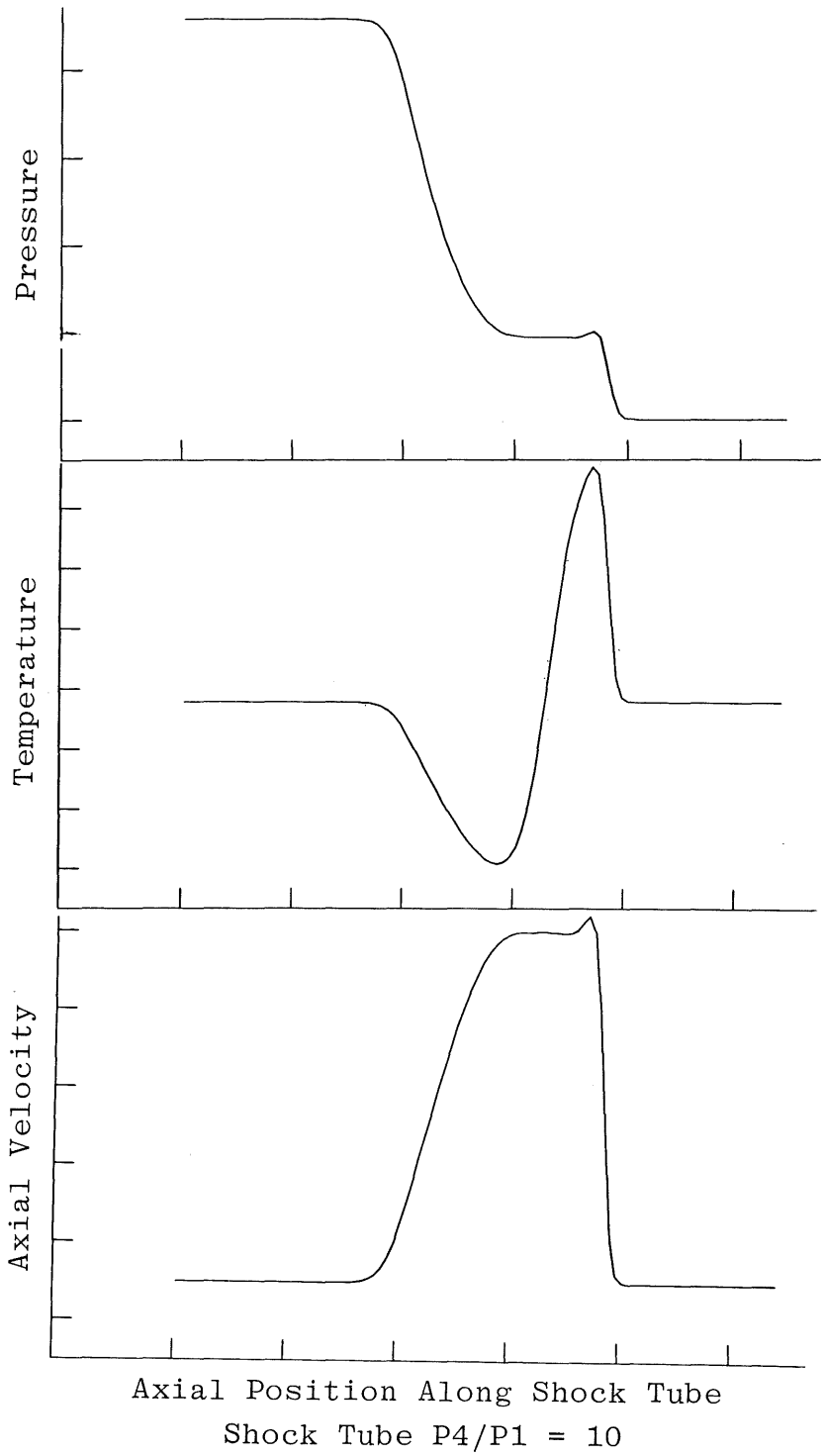


Fig. 16 Shock Tube Results

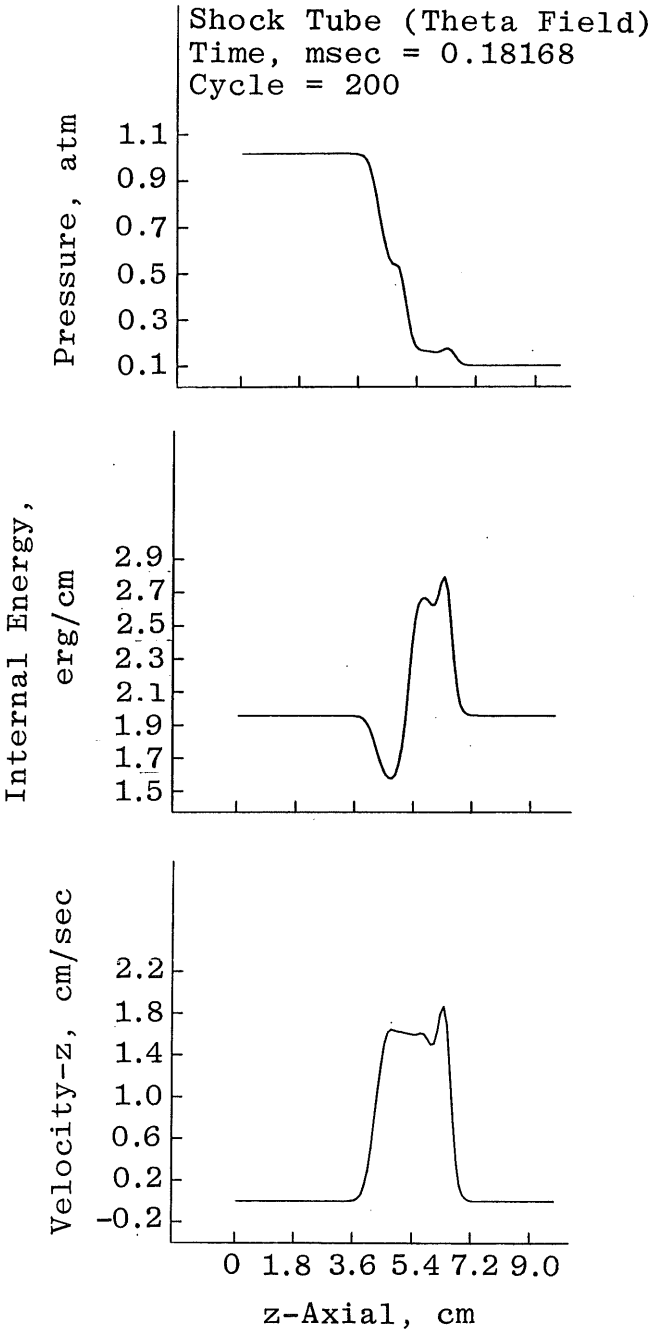


Fig. 16 (Continued)

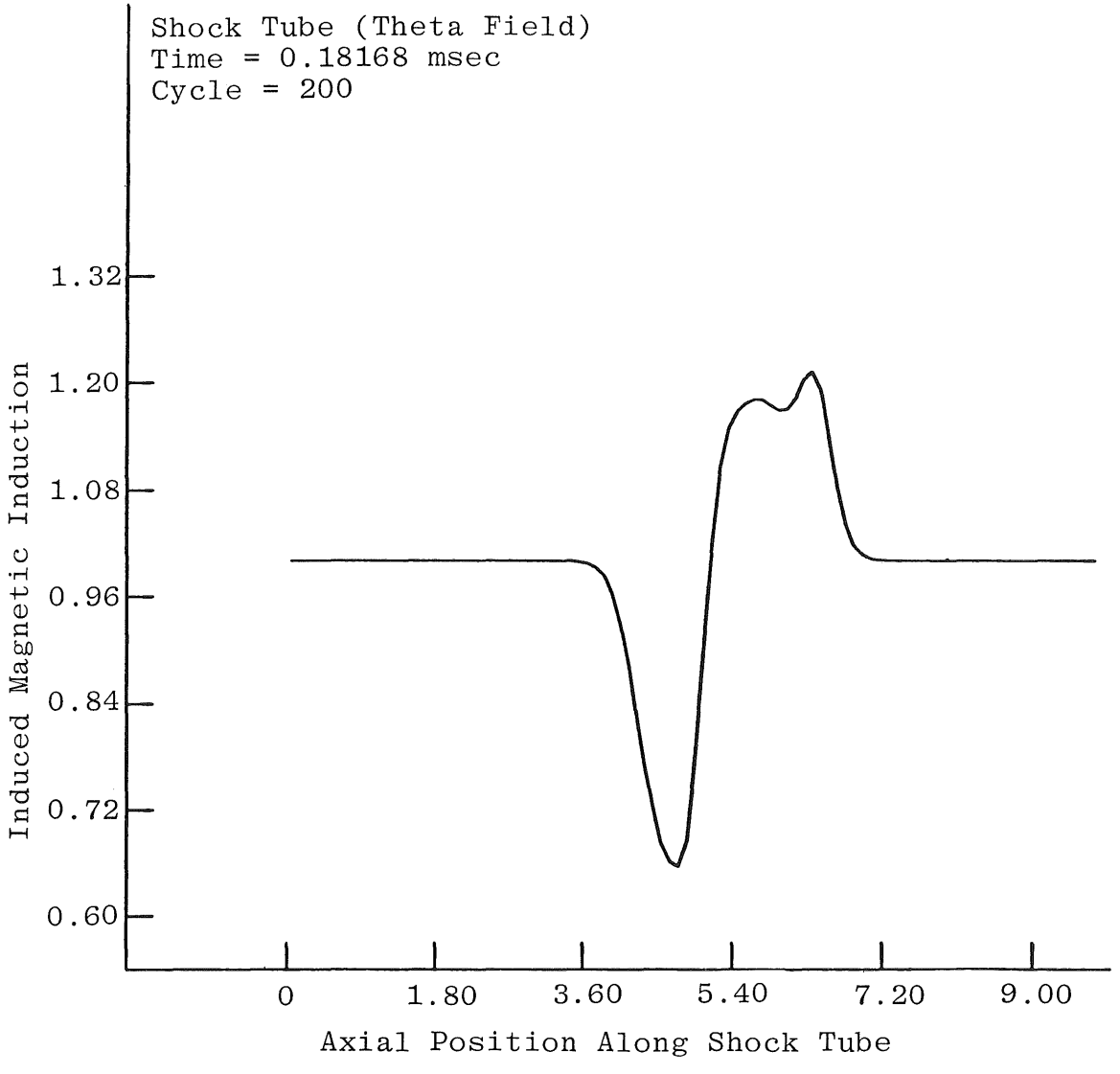


Fig. 16 (Continued)

$$C_s = a_1\left(\frac{(\gamma-1)}{2\gamma} + \frac{(\gamma+1)}{2\gamma}\frac{p_2}{p_1}\right)^{1/2} \tag{171}$$

$$\frac{p_4}{p_1} = \frac{p_2}{p_1}\left[1-\frac{(\gamma-1)(a_1/a_4)(p_2/p_1-1)}{\mathrm{SQRT}\{(2\gamma)(2\gamma+(\gamma+1)(p_2/p_1-1))\}}\right]^{\frac{-2\gamma}{\gamma-1}} \tag{172}$$

ratio (p_4/p_1) = 10 and temperature ratio (T_4/T_1) = 1, will generate a shock moving into the lower pressure region at a speed of 52,800 cm/sec and produce a particle velocity = 28,400 cm/sec (p_2/p_1 is 2.86). Numerical results indicate a shock speed of approximately 53,600 cm/sec and pressure ratio of 2.98. A temperature and density ratio across the shock was numerically found to be 1.40 and 2.13, which compares favorably with 1.405 and 2.07, respectively, as predicted by theory. Computing upstream and downstream Mach numbers relative to the moving shock:

$$M_x = C_s/c_2 = 53{,}600/33{,}000 = 1.625$$

where $c = (\gamma p/\rho)^{\frac{1}{2}}$

$$M_y = (C_s-U_p)/c_1 = (53{,}600-28{,}400)/39{,}000 = 0.66$$

Table (1) compares the computed values of ρ_2/ρ_1, p_2/p_1, T_2/T_1, M_2/M_1, Up and C_s with one-dimensional normal shock relations or the Rankine-Hugoniot equations and shows close agreement in all cases.

Table (1) Comparison of Results for Mx = 1.625

	Numerical Calculation	Rankine-Hugoniot Relations
M_x	1.625	1.625 (GIVEN)
M_y	0.665	0.66
p_2/p_1	2.98	2.92
ρ_2/ρ_1	2.13	2.07
T_2/T_1	1.40	1.405

Modifying the shock equations so as to introduce magnetic fields, the following equations result:

MHD Shock Relations in a Moving Coordinate System

$$\rho_1 u = \rho_2 (u-u_2) \tag{173}$$

$$p_1 + \frac{B_1^2}{2\mu_p} + \rho_1 u^2 = p_2 + \frac{B_2^2}{2\mu_p} + \rho_2 (u-u_2)^2 \tag{174}$$

$$\rho_1 u\left[\frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1} + \frac{B_1^2}{\rho_1 \mu_p} + \frac{u^2}{2}\right] = \rho_2 (u-u_2)\left[\frac{\gamma}{\gamma-1}\frac{p_2}{\rho_2} + \frac{B_2^2}{\rho_2 \mu_p} + \frac{1}{2}(u-u_2)^2\right] \tag{175}$$

u = shock speed

u_2 = particle velocity

B = magnetic induction

P = pressure

μ_p = magnetic permeability

ρ = density

C_s = shock velocity

γ = specific heat ratio

For an applied magnetic field strength of 1 Tesla, the values of pressure, temperature and velocity are modified as shown in Figure (16b) and (16c). Preservation of the Rankine-Hugoniot equations which indicates conservation of mass, momentum and energy through a normal shock was maintained.

Regular-Irregular Shock Reflection

Regular-irregular shock reflection has been studied most recently by numerous authors (90, 91, 92 and 93). Theory governing the transition from regular reflection (the formation of a reflected oblique

shock from an incident oblique shock) to irregular reflection (the formation of two oblique shocks and a normal shock) has been established. The principal objective in performing this calculation was to determine the program's effectiveness in computing a stable Mach stem or triple point. No attempt was made to study the extremely difficult and (computer) time consuming problems of repetitive triple point formation, especially those emanating from an under-expanded or over-expanded nozzle. Figures (17), (18), (19) and (20) illustrate the formation of this Mach stem. In Figure (17), velocity vectors depict the shock pattern. In Figures (18) and (19), pressure and Mach intensities are shown. Pressure contours are displayed in Figure (20) and finally the normal shock of the Mach stem is plotted in Figure (21). A triple point was also computed from flow exhausting from a nozzle as shown in Figure (22).

Other calculations include a detached bow shock over a semi-infinite cylinder as displayed in Figure (23), and a re-entry vehicle with a configuration (point of inflection) causing an imbedded shock (Figure (24)).

3.2 Boundary Layer

The most fundamental boundary layer problems investigated are (1) Couette flow, (2) viscous flow over a flat plate, (3) Rayleigh flow discussed in Section (3.4), and (4) turbulence.

Couette flow consists of flow in a parallel-wall channel where one wall is stationary and the other is moving. Two problems are examined: (1) the fluid is non-conducting and experiences only pressure and viscous forces and (2) the fluid is conducting and experiences pressure,

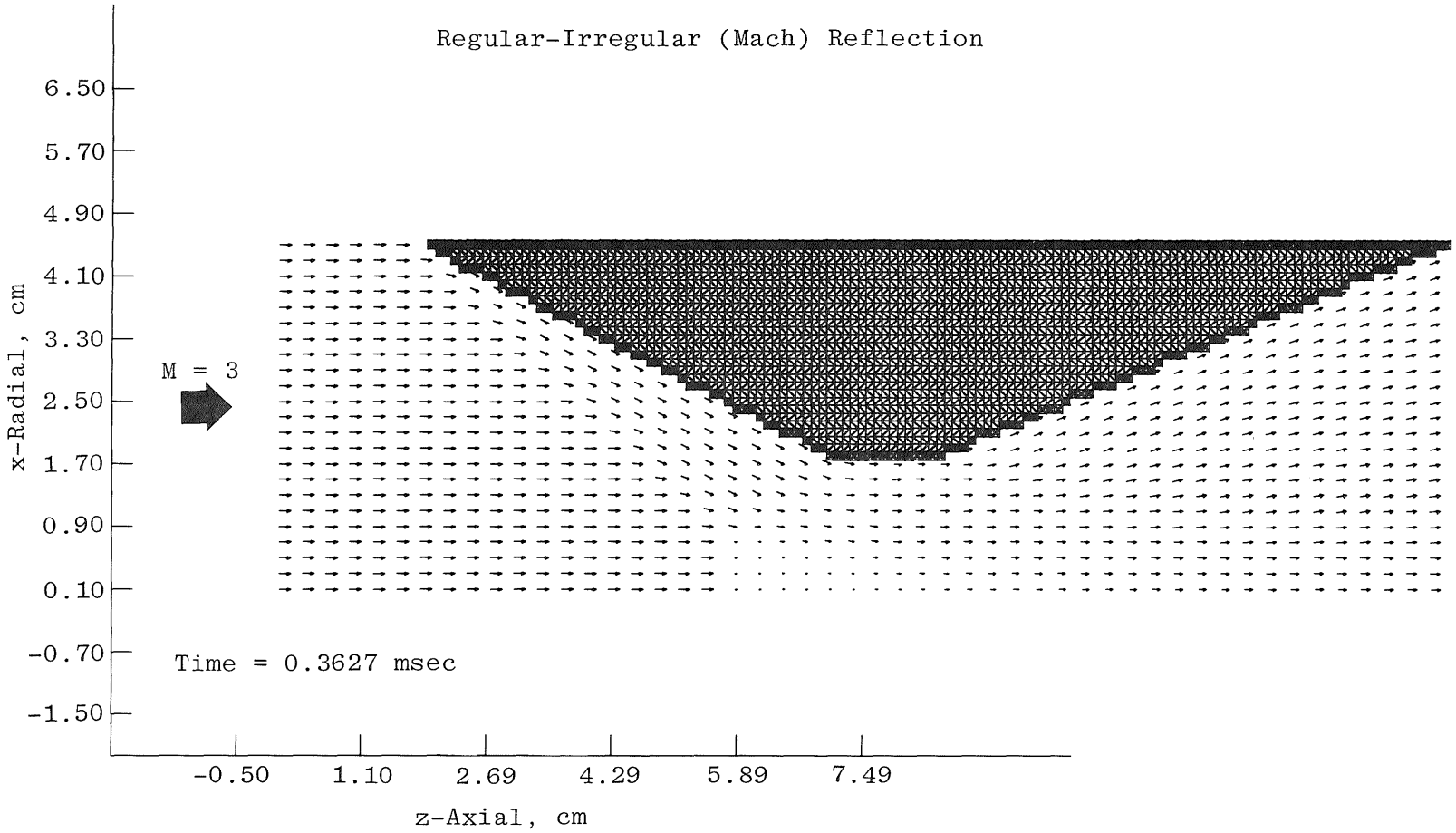


Fig. 17 Velocity Vectors of Irregular (Mach) Reflection

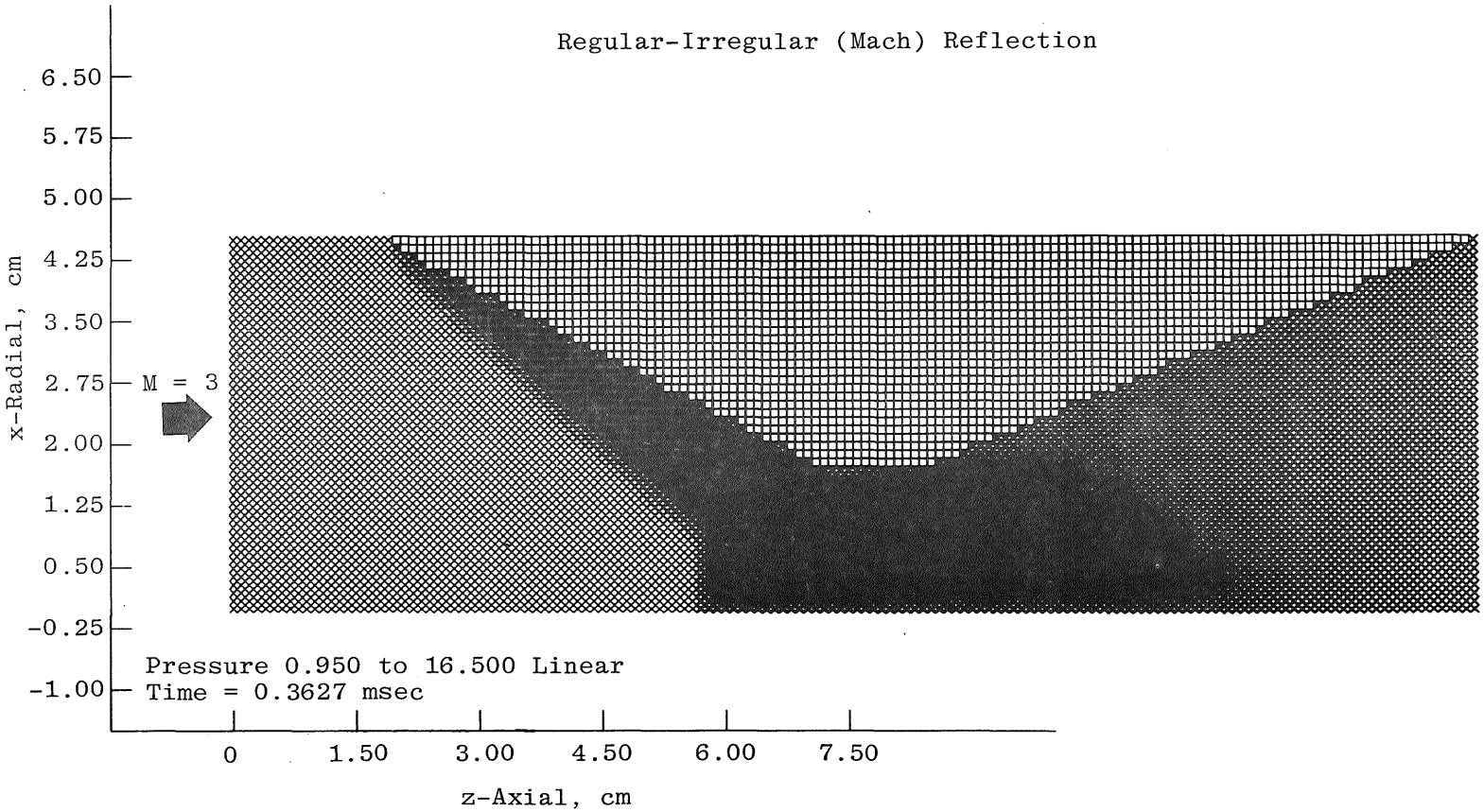


Fig. 18 Pressure Intensity (Shade) of Mach Stem

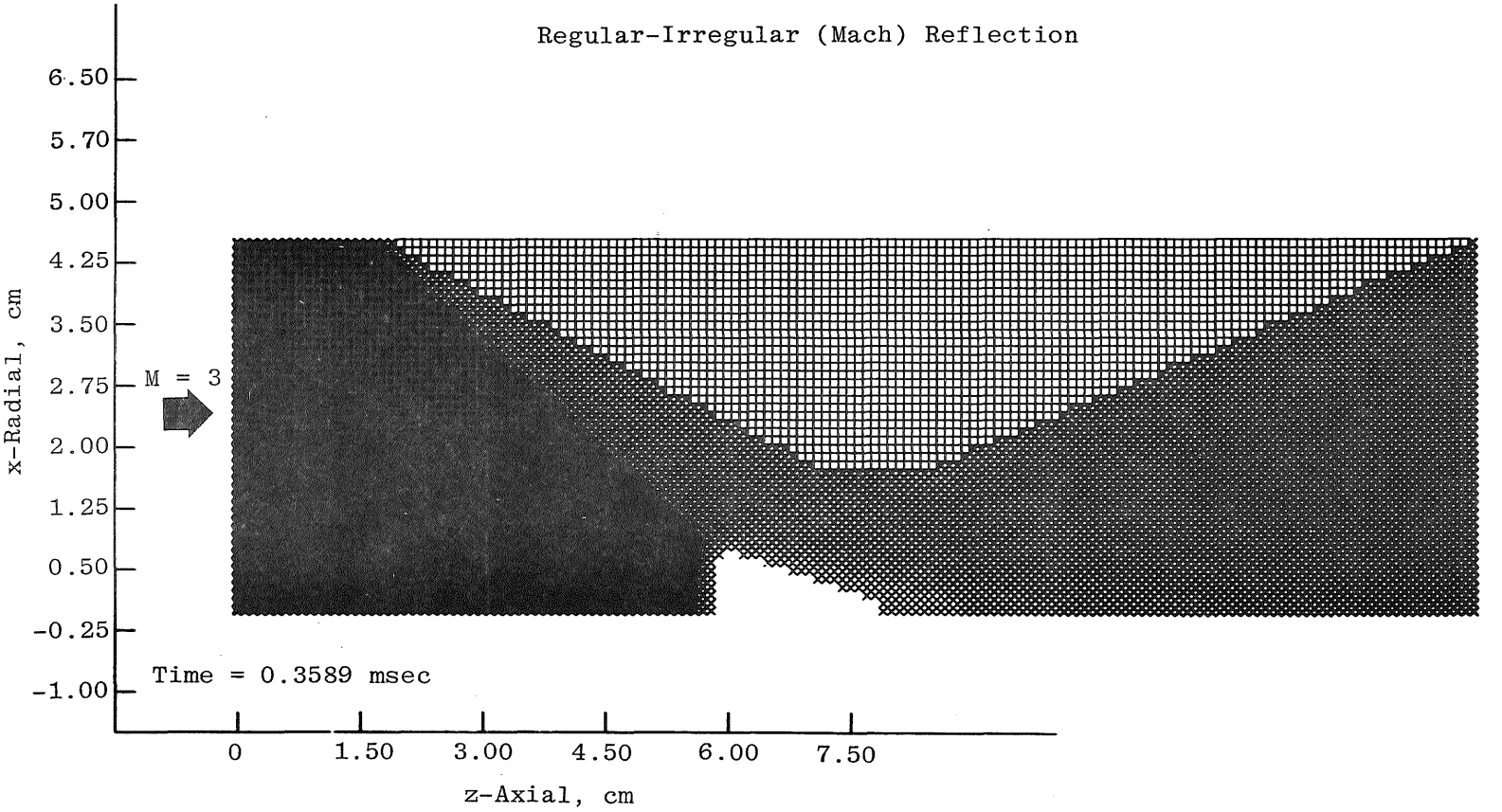


Fig. 19 Mach Number Intensity (Shade) of Mach Stem

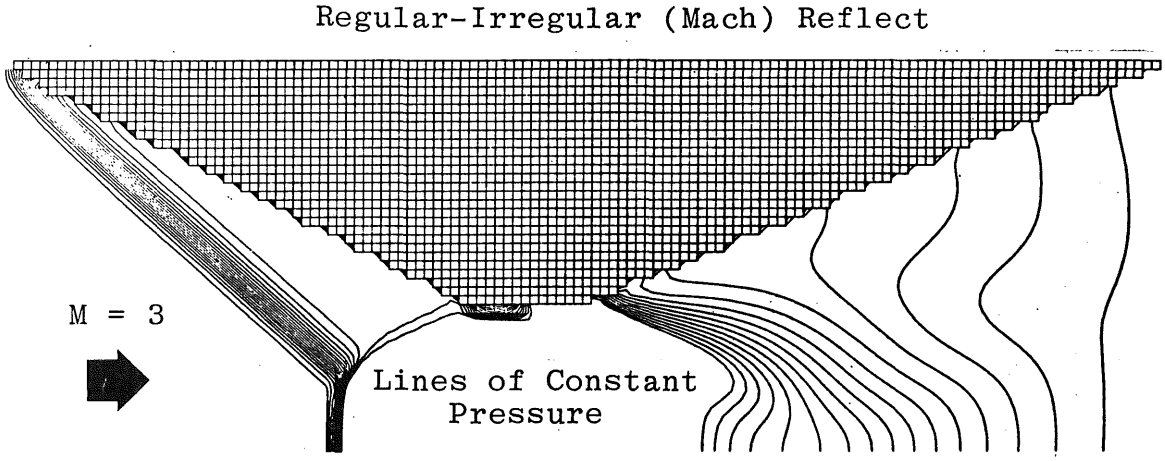


Fig. 20 Pressure Contours of Mach Stem

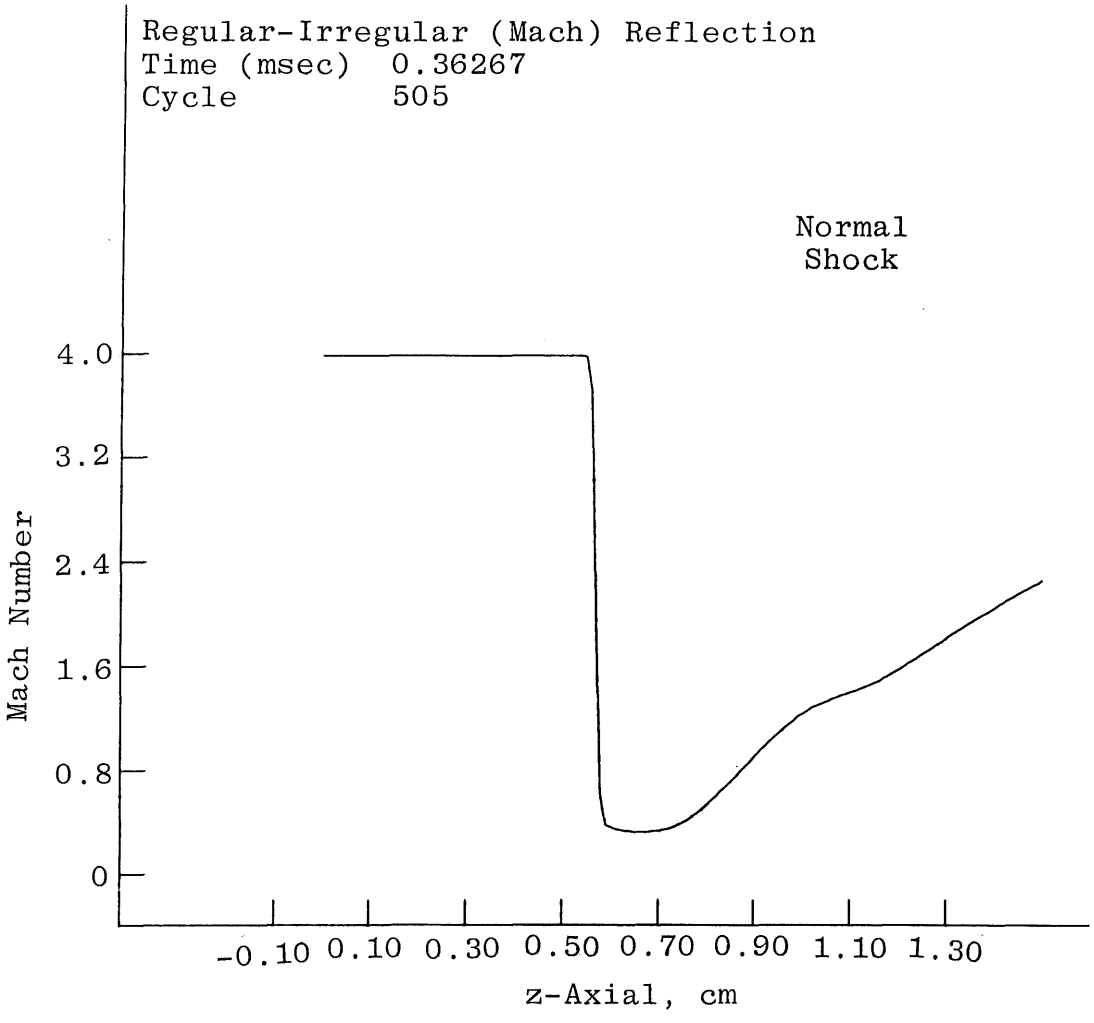


Fig. 21 Normal Shock of Mach Stem

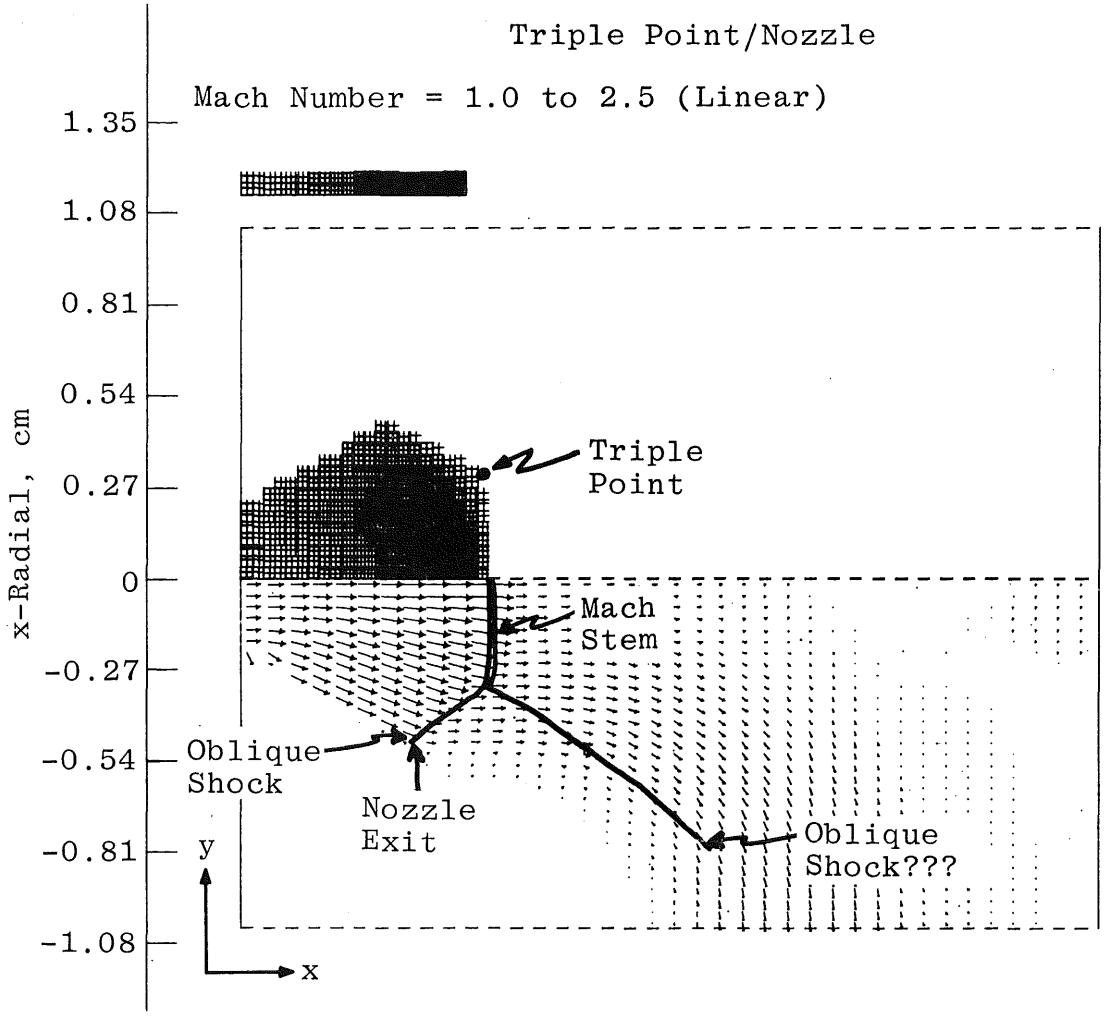


Fig. 22 Triple Point Emanating from a Nozzle

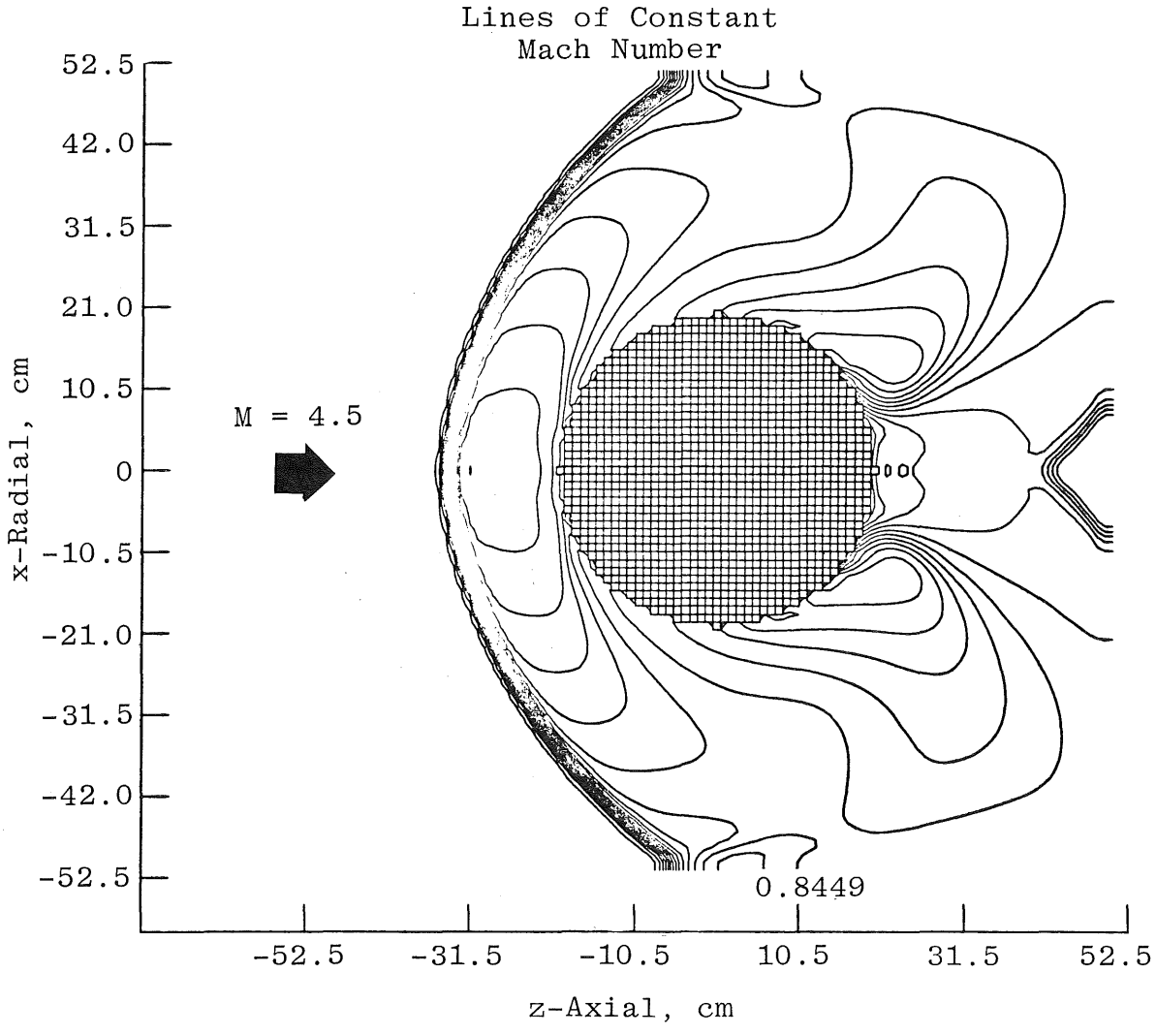


Fig. 23 Bow Shock over a Semi-Infinite Cylinder

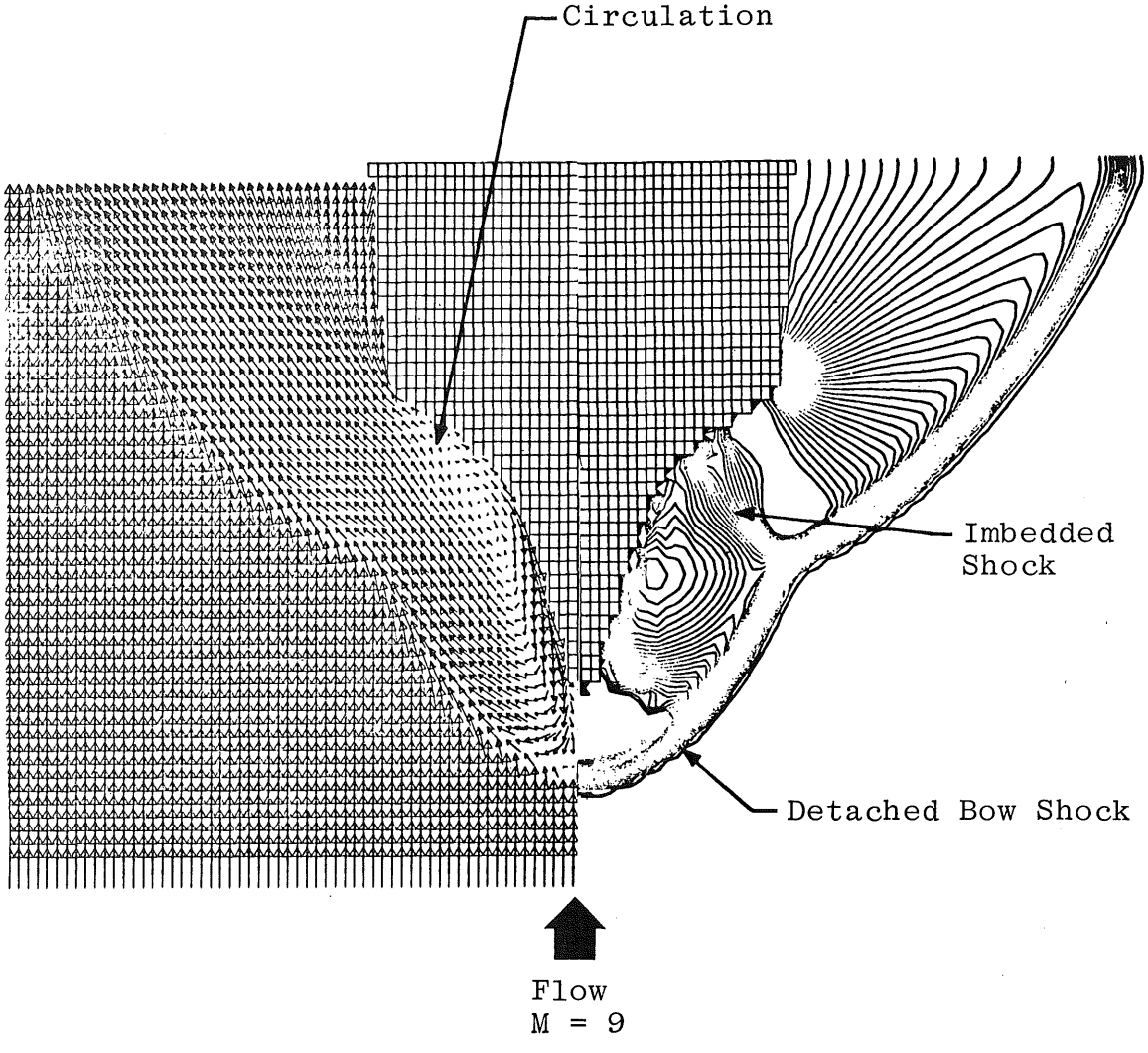


Fig. 24 Interacting Shocks off a Re-Entry Vehicle

viscous and Lorentz forces when under the influence of an applied magnetic field.

Couette Flow

Considering a non-conducting incompressible fluid, the equation of motion in the x-direction reduces to:

$$\rho\frac{\delta}{\delta t}(u) = -\frac{\delta}{\delta z}(p)+\mu\frac{\delta}{\delta r}(\frac{\delta}{\delta r}(u)) \tag{176}$$

At steady state, Equation (176) becomes:

$$\frac{\delta}{\delta z}(p) = \mu\frac{\delta}{\delta r}(\frac{\delta}{\delta r}(u)) \tag{177}$$

Applying the following boundary conditions:

$u = 0,\ r = 0;\ u = U,\ r = \infty$

a solution of the form

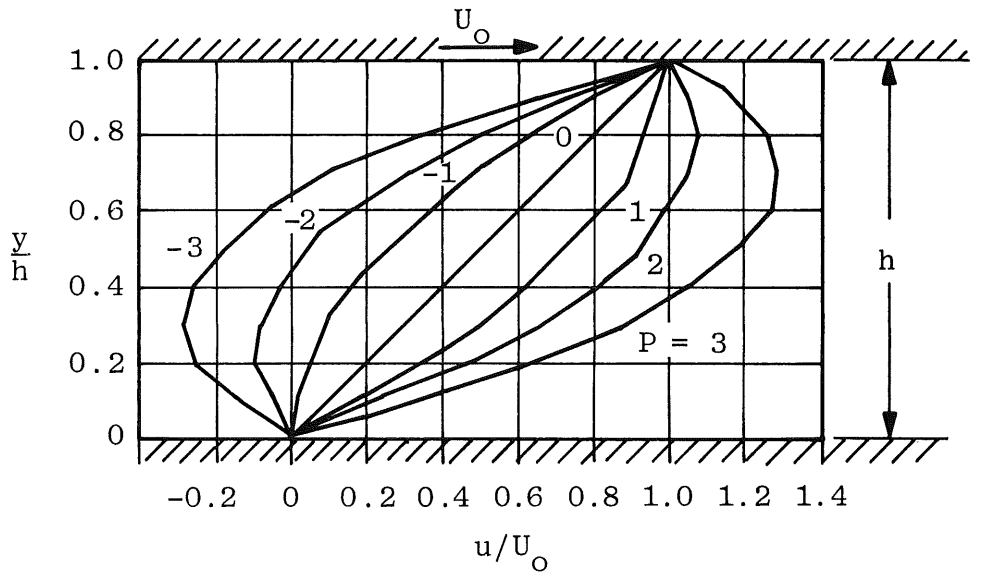
$$u = \frac{r}{h}[1-(1-\frac{r}{h})P] \tag{178}$$

is obtained, where:

$$P = \frac{h^2}{2\mu U}\ (-\frac{\delta}{\delta z}(p)) \tag{179}$$

The cases for P = -3, -2, -1 (backflow), 0 (constant pressure), +1, +2 and +3 were run with results in close agreement with Schlicting (94). A disparity of approximately 10% was caused by a coarse mesh (ten cells) and a slightly varying time-dependent solution (Figure (25)).

Next, considering the transient Couette problem (Stokes' First Problem) at a constant pressure, and applying the same initial and boundary conditions as before, the transient solution is developed. Results are shown in Figure (25) with good comparison to the data presented in Schlicting (94).



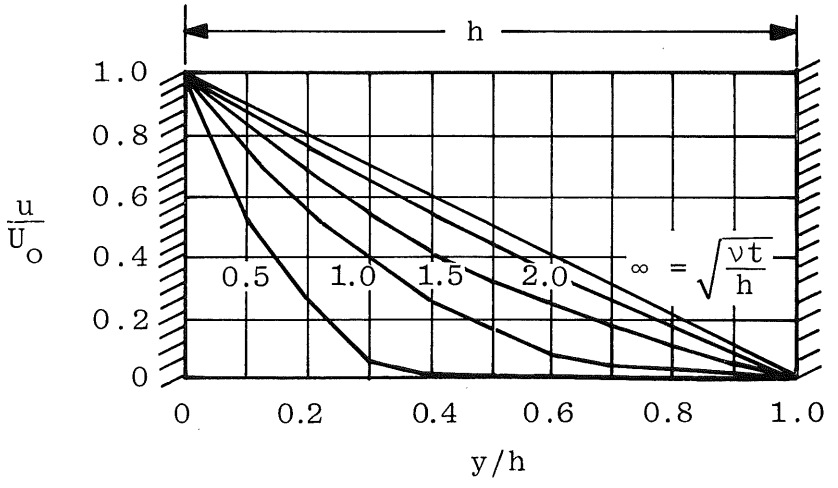


Fig. 25 Couette Flow. Transient and Steady State

Couette Flow - Thermal Distribution

The temperature distribution in Couette flow is governed by the energy equation and reduces to:

$$0 = -\lambda\frac{\delta}{\delta t}\left(\frac{\delta}{\delta t}(T)\right)+\mu\left\{\frac{\delta}{\delta t}(u)\right\}\left\{\frac{\delta}{\delta t}(u)\right\} \tag{180}$$

for the 1-D, steady case with constant thermal conductivity and viscosity. If both walls are maintained at constant temperature T_w then the solution of Equation (180) is parabolic and its analytic solution is shown in Table (2) along with numerical results.

Table (2) Thermal Distribution in Couette Flow

X/L	T/TW Analytic	T/TW Numerical
0.	1.0000	1.0000
0.1	1.3600	1.3600
0.2	1.6400	1.6397
0.3	1.8400	1.8394
0.4	1.9600	1.9590
0.5	2.0000	1.9988
0.6	1.9600	1.9587
0.7	1.8400	1.8388
0.8	1.6400	1.6391
0.9	1.3600	1.3595
1.0	1.0000	1.0000

Couette - MHD Flow

The equation of motion in the axial direction (neglecting radial momentum) is given by:

$$\frac{\delta}{\delta t}(u)+u\frac{\delta}{\delta z}(u)+v\frac{\delta}{\delta r}(u) = -\frac{1}{\rho}\frac{\delta}{\delta z}(p)+\frac{1}{\rho}\frac{\delta}{\delta r}\left(\mu\frac{\delta}{\delta r}(u)\right)+\frac{1}{\rho}\bar{j}x\bar{B} \tag{181}$$

Employing Ohm's Law, the Lorentz force $\bar{j}x\bar{B}$ is replaced by

$$\bar{j}x\bar{B} = \frac{\nabla xB_z\bar{k}}{\mu}x\bar{B} = -\frac{1}{\mu}\frac{\delta}{\delta r}(B_z\bar{B}) \tag{182}$$

where $\bar{k}$ is the unit normal vector

where B_z is the induced magnetic field and B is the applied magnetic field. Also, from the magnetic induction equation

$$\frac{\delta}{\delta t}(\bar{B}_z) = \frac{\nabla x \nabla x B_z \bar{k}}{\mu\sigma} + \nabla x \bar{v} x B_z \bar{k} \tag{183}$$

at steady state, this equation reduces to:

$$\frac{1}{\sigma\mu}\frac{\delta}{\delta r}\left(\frac{\delta}{\delta r}(B_z)\right) = \frac{\delta}{\delta r}(uB_z) \tag{184}$$

and upon integration yields:

$$\frac{1}{\mu}\frac{\delta}{\delta r}(B)B_z = \sigma u B_z^2 \tag{185}$$

The Lorentz force then becomes uB_z^2 and the equation of motion at steady state (constant viscosity) reduces to:

$$\frac{\mu}{\rho}\frac{\delta}{\delta r}\left(\frac{\delta}{\delta r}(u)\right) = \frac{\delta}{\delta r}(p) + \sigma u B_z^2 \tag{186}$$

with boundary conditions:

$u = u\ (r = 0)$, $u = 0\ (r = h)$

Non-dimensionalizing u and r to the free stream velocity and channel width, respectively, the solution to Equation (186), neglecting the pressure gradient, is

$$u = \frac{\mathrm{SINH}(H_a Y)}{\mathrm{SINH}(H_a)} \tag{187}$$

$$B_z = \frac{\mathrm{COSH}(H_a) - \mathrm{COSH}(H_a Y)}{\mathrm{SINH}(H_a)} \tag{188}$$

where H_a is the Hartmann number

$$H_a^2 = \frac{\sigma B_o^2 h^2 \rho}{\mu} \tag{189}$$

U is the non-dimensional velocity and Y is the non-dimensional width. As H_a goes to zero

$$u = \frac{H_a Y}{H_a} = Y \tag{190}$$

If B_z also vanishes the solution for couette flow results.

Comparison of numerical and analytic results are shown in Table (3) with good agreement in all cases.

Table (3) Couette Flow with a Transverse Magnetic Flow

	Analytic Solution		Numerical Solution†	
y/h	u/U_o	B*	u/U_o	B*
0.0	0.	0.240	0.	0.243
0.1	0.02	0.240	0.025	0.243
0.2	0.05	0.238	0.051	0.241
0.3	0.08	0.234	0.081	0.238
0.4	0.12	0.230	0.118	0.230
0.5	0.18	0.220	0.166	0.219
0.6	0.22	0.200	0.234	0.205
0.7	0.30	0.170	0.330	0.178
0.8	0.44	0.120	0.472	0.142
0.9	0.69	0.070	0.683	0.086
1.0	1.00	0.	1.00	0.

B* ≡ normalized induced magnetic field

†flow not exactly steady or incompressible

Flat PLate

The boundary layer along a flat plate (Figure (26)) is described by the following boundary layer equations and boundary conditions:

$$u\frac{\delta}{\delta z}(u)+v\frac{\delta}{\delta r}(u) = \frac{\mu}{\rho}\frac{\delta}{\delta r}\left(\frac{\delta}{\delta r}(u)\right) \tag{191}$$

$$\frac{\delta}{\delta z}(u)+\frac{\delta}{\delta r}(v) = 0 \tag{192}$$

$$r = 0 \, , u = v = 0 \, ; r = \infty \, , u = u_\infty \tag{193}$$

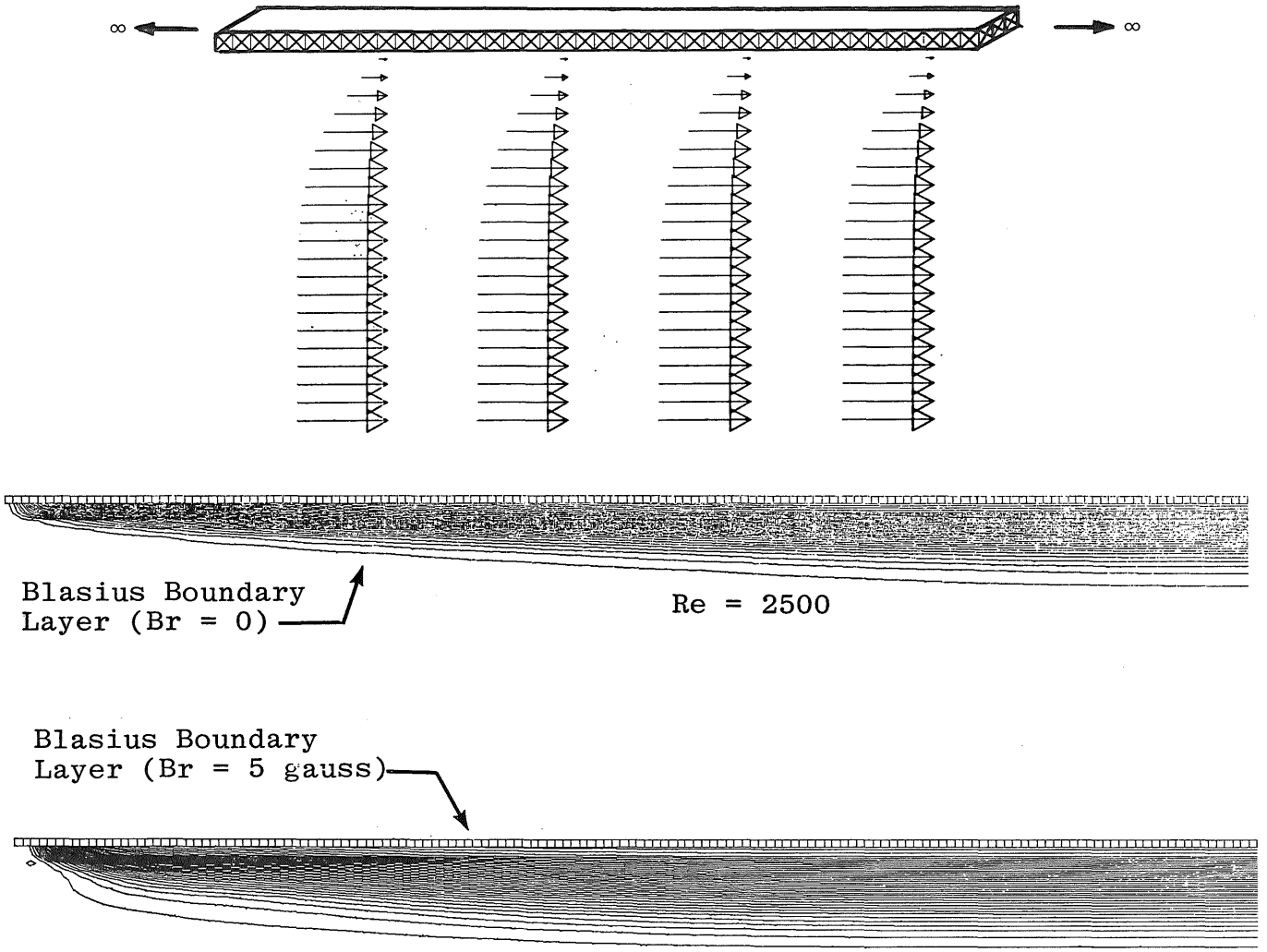


Fig. 26 Laminar Boundary Layer over a Flat Plate

Blasius developed a series solution to the transformed ordinary differential equation which replaced the partial differential equations described above.

Blasius predicted a boundary layer thickness δ equal to $5x/Re_x^{-1}$. In Figure (26) numerical results for the case where $\rho = 0.001$ gm/cm^3, $\mu = 0.0001$ cp, $u = 833$ cm/sec are shown. The boundary layer thickness at $x = 0.048$ cm was found to be 0.011 cm which compares favorably with the Blasius prediction of 0.01 cm.

MHD Flow over a Flat Plate

Incompressible viscous flow over a flat plate in the presence of a transverse magnetic field was investigated by Rossow (33). The flow in the boundary layer is described by:

$$\rho\left(u\frac{\delta}{\delta z}(u)+v\frac{\delta}{\delta r}(u)\right)+\frac{\delta}{\delta z}(p) = -\sigma B_z^2 u+\frac{\delta}{\delta r}\left(\mu\frac{\delta}{\delta r}(u)\right) \tag{194}$$

and in the inviscid free stream:

$$\frac{\delta}{\delta z}(p) = -\sigma B_z^2 u \quad \frac{\delta}{\delta z}(u) = 0 \tag{195}$$

and with boundary conditions

$u = 0$, $y = 0$; $u = u$, $y = \pi$.

Applying an external magnetic field to the previously discussed flat plate problem, and assuming now that the fluid is electrically conducting, the boundary layer becomes distorted as shown in Figure (26).

Turbulent Jet

The equations of motion applied to a turbulent problem are:

$$\frac{\delta}{\delta t}(u)+u\frac{\delta}{\delta z}(u)+v\frac{\delta}{\delta r}(u) = \frac{1}{\rho}\frac{\delta}{\delta r}(\tau) \tag{196}$$

$$\frac{\delta}{\delta z}(u) + \frac{\delta}{\delta r}(v) = 0 \tag{197}$$

Schlicting discusses the free turbulent jet flow problem (Figure (27)) and presents theoretical results of Gortler and measurements made by Reichardt. Employing a virtual kinematic viscosity based on the Prandtl hypothesis:

$$\varepsilon = \rho\lambda^2_E\delta\frac{\delta}{\delta r}u = Ax(U_1 - U_2) \tag{198}$$

where U_1 and U_2 are velocities of two mixing streams. The equations of motion for the steady case reduce to:

$$u\frac{\delta}{\delta z}(u) + v\frac{\delta}{\delta r}(u) = \varepsilon\frac{\delta}{\delta r}\left(\frac{\delta}{\delta r}(u)\right) \tag{199}$$

Solution of this equation by similarity transformation yields an equation identical to that of the Blasius equation for a flat plate, but with different boundary conditions. Based on measurements performed by Reichardt (A is evaluated) an eddy kinematic viscosity is computed from empirical data and excellent results between theory and experiment were obtained. The solution to the Blasius equation is the error function, and u was found to be:

$$u = \frac{(U_1+U_2)}{2}\left\{1 + \frac{U_1-U_2}{U_1+U_2}\mathrm{ERF}(\varepsilon)\right\};\ \varepsilon = \sigma\frac{r}{z} \tag{200}$$

This problem was solved numerically and results are compared with those of Gortler and Reichardt in Figures (28) and (29).

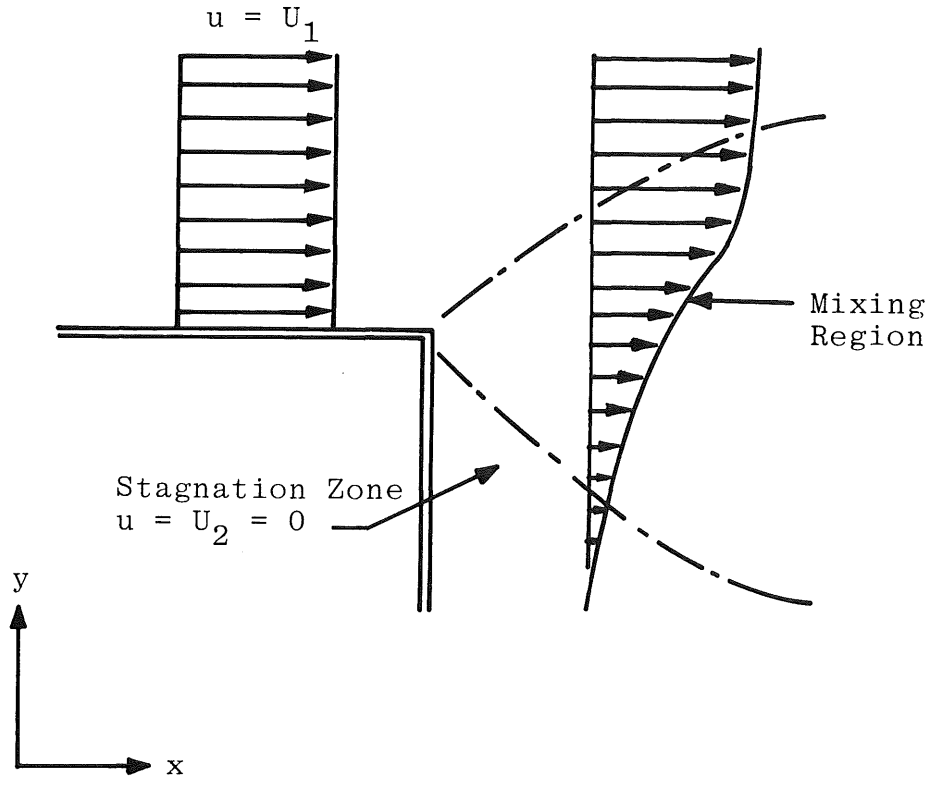


Fig. 27 Free Jet Turbulent Flow (Mixing Resulting Entirely from Turbulence, p = 0)

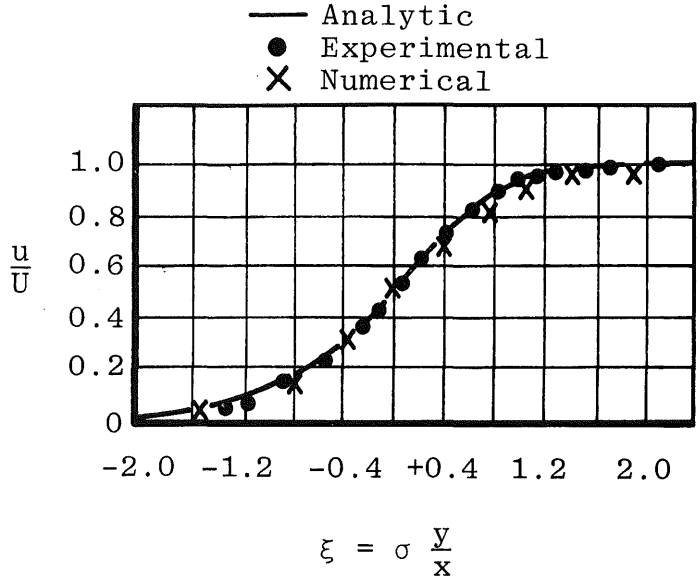


Fig. 28 Experimental and Numerical Data for Free Jet Turbulent Flow

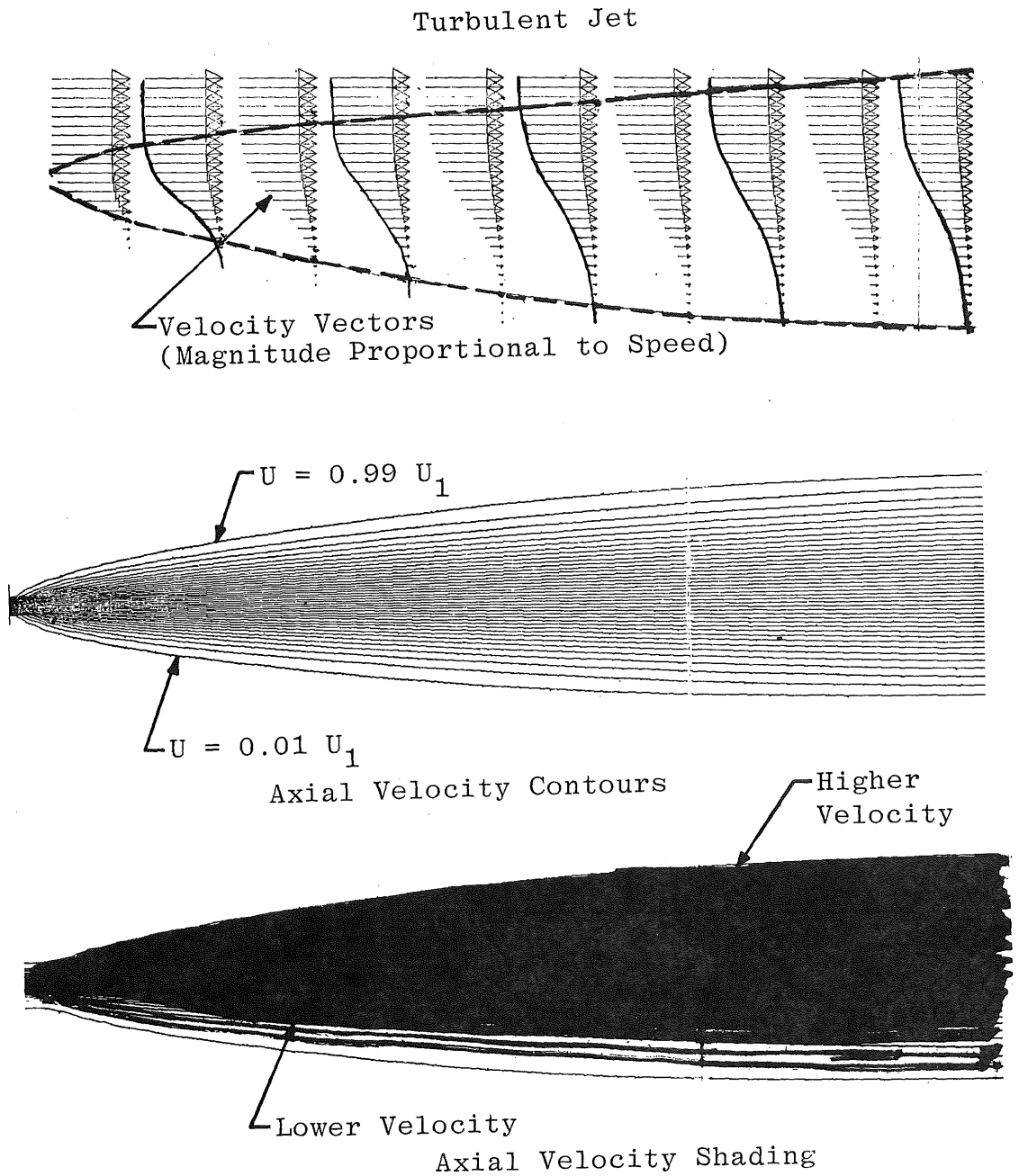


Fig. 29 Numerical Results for Free Jet Turbulent Flow

3.3 Compressible Flow

Compressible flow problems consisted of internal flow in a nozzle and external flow around an RV and M-117 warhead.

Nozzle Flow

Flow in a nozzle was investigated with attention focused on the phenomena of choking, shocks and flow separation.

Analytic solutions to certain one-dimensional gas dynamic problems are easily developed. For a perfect gas, isentropic flow and varying area, the conservation equations yield the following thermodynamic relations:

$$\frac{p_o}{p_x} = \left(1+ \frac{\gamma-1}{2} M_x\right)^{\gamma/(\gamma-1)} \tag{201}$$

$$\frac{\rho_o}{\rho_x} = \left(1+ \frac{\gamma-1}{2} M_x\right)^{1/(\gamma-1)} \tag{202}$$

$$\frac{T_o}{T_x} = \left(1+ \frac{\gamma-1}{2} M_x\right) \tag{203}$$

$$\frac{A_y}{A_x} = \frac{M_x}{M_y}\left(\frac{T_x}{T_y}\right)^{1/2} \tag{204}$$

where P,ρ,T,A and M denote pressure, density, temperature, area and Mach number, respectively, at chamber conditions (o) or stations (x) and (y).

Considering flow at constant area, the conservation equations become:

$$\rho_1 u_1 = \rho_2 u_2 \tag{205}$$

$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2 \tag{206}$$

$$H_1 + \frac{u_1^2}{2} = H_2 + \frac{u_2^2}{2} \tag{207}$$

where H_1 and H_2 are the total enthalpy per unit mass. Equations (205) through (207) hold before and after the shock. Equations (205) and (207) are valid for Fanno Flow (friction), whereas Equations (205) and (206) are satisfied for Reyleigh flow (heat transfer).

For a normal shock these equations are rearranged to yield the Rankine-Hugoniot expressions:

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1) \tag{208}$$

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+2} \tag{209}$$

$$\frac{p_{o_2}}{p_{o_1}} = \left[1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1)\right]^{1/(1-\gamma)} \left[\frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+1}\right]^{\frac{\gamma}{\gamma-1}} \tag{210}$$

A fundamental problem of obvious considerable importance to the aerospace engineer is flow in a nozzle where the inviscid equations described above hold. Problems investigated in this section concern compressible, inviscid flow where choking, shocks and heat and pressure losses are experienced.

Nozzle flow was examined for choking; flow separation; stationary shocks; and 1-D influence of area change on pressure, density and

temperature. A 2-D calculation was performed with a chamber to ambient pressure ratio of 11.6. Table (4) compares the isentropic Mach number and the pressure, density and temperature ratios to the area ratio for both analytic (1-D) and numerical (2-D) results (see Figure (30)). Conditions at the throat were found to be M = 1., p/p_o = 0.45, T/T_o = 0.90, ρ/ρ_o = 0.5 which agrees within 10-20% of the 1-D analytic solutions. The 2-D effects, although not severe, are significant enough to be considered in future calculations.

Table (4) Isentropic Conditions in the Nozzle

Z	ρ	U	P	T	M
axial position					
0.0	0.0150	0	11.59	117.2	0
0.2	0.0105	7515	8.04	116.6	0.228
0.4	0.0104	6411	8.25	120.1	0.191
0.6	0.0106	5352	8.58	122.9	0.159
0.8	0.0106	5110	8.68	124.6	0.150
1.0	0.0105	5465	8.67	124.9	0.169
1.2	0.0104	6227	8.65	125.7	0.182
1.4	0.0104	7335	8.64	125.9	0.214
1.6	0.0104	8783	8.61	126.0	0.256
1.8	0.0103	10619	8.54	126.0	0.310
2.0	0.0101	12934	8.40	125.8	0.377
2.2	0.00981	15846	8.11	125.3	0.463
2.4	0.00931	19523	7.62	124.1	0.573
2.6	0.00853	24190	6.85	121.8	0.717
2.8	0.00744	29261	5.78	117.4	0.882
throat					
3.0	0.00639	33854	4.75	112.9	1.041
3.2	0.00549	37800	3.91	108.1	1.188
3.4	0.00473	41254	3.24	103.8	1.324
3.6	0.00407	44414	2.67	99.6	1.455
3.8	0.00348	47371	2.19	95.5	1.585
4.0	0.00296	50139	1.78	91.5	1.715
4.2	0.00252	52709	1.46	87.6	1.841
4.4	0.00215	55071	1.19	84.1	1.964
4.6	0.00185	57215	0.985	80.9	2.079
4.8	0.00161	58896	0.8333	78.45	2.175

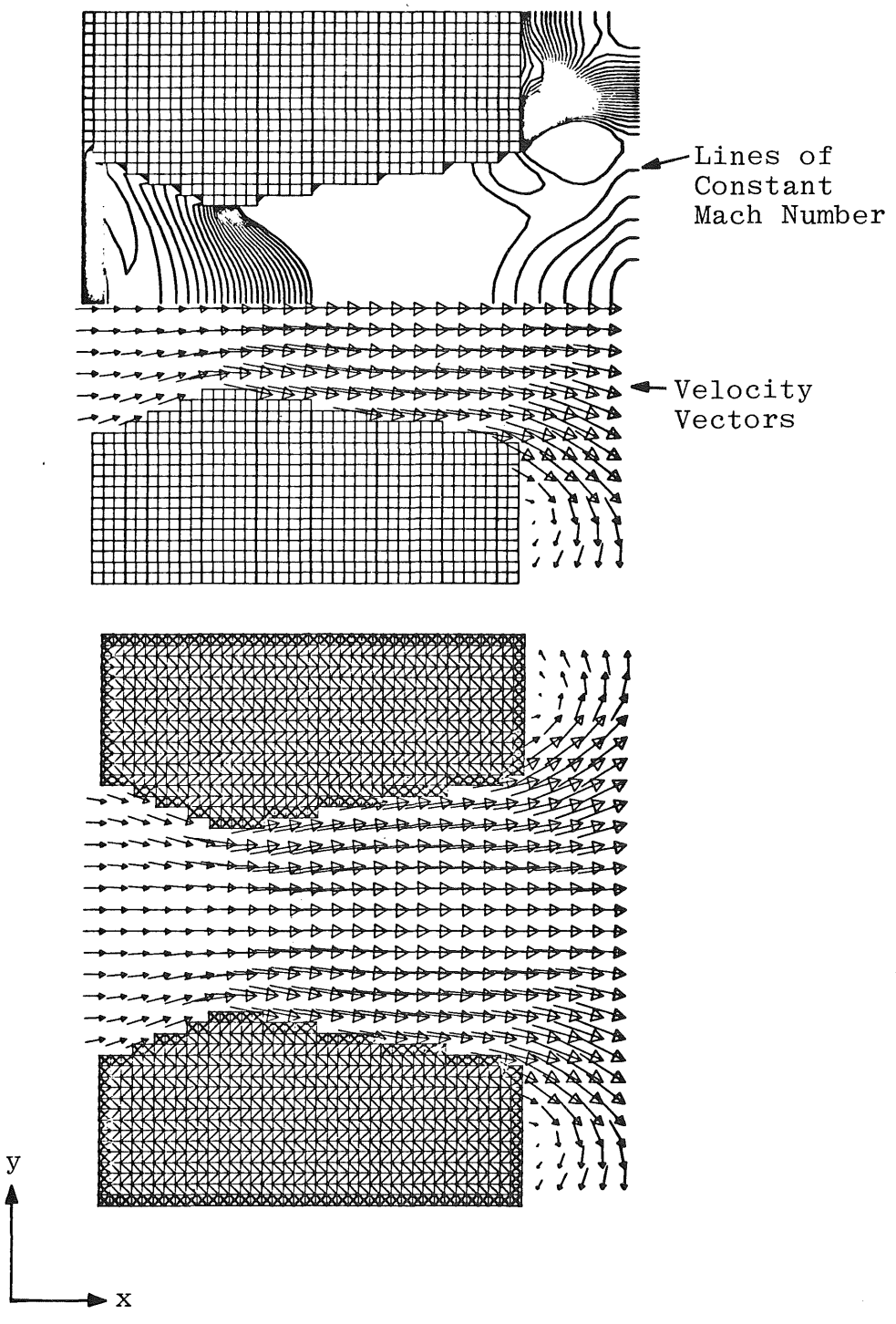


Figure 30 Isentropic Nozzle Flow

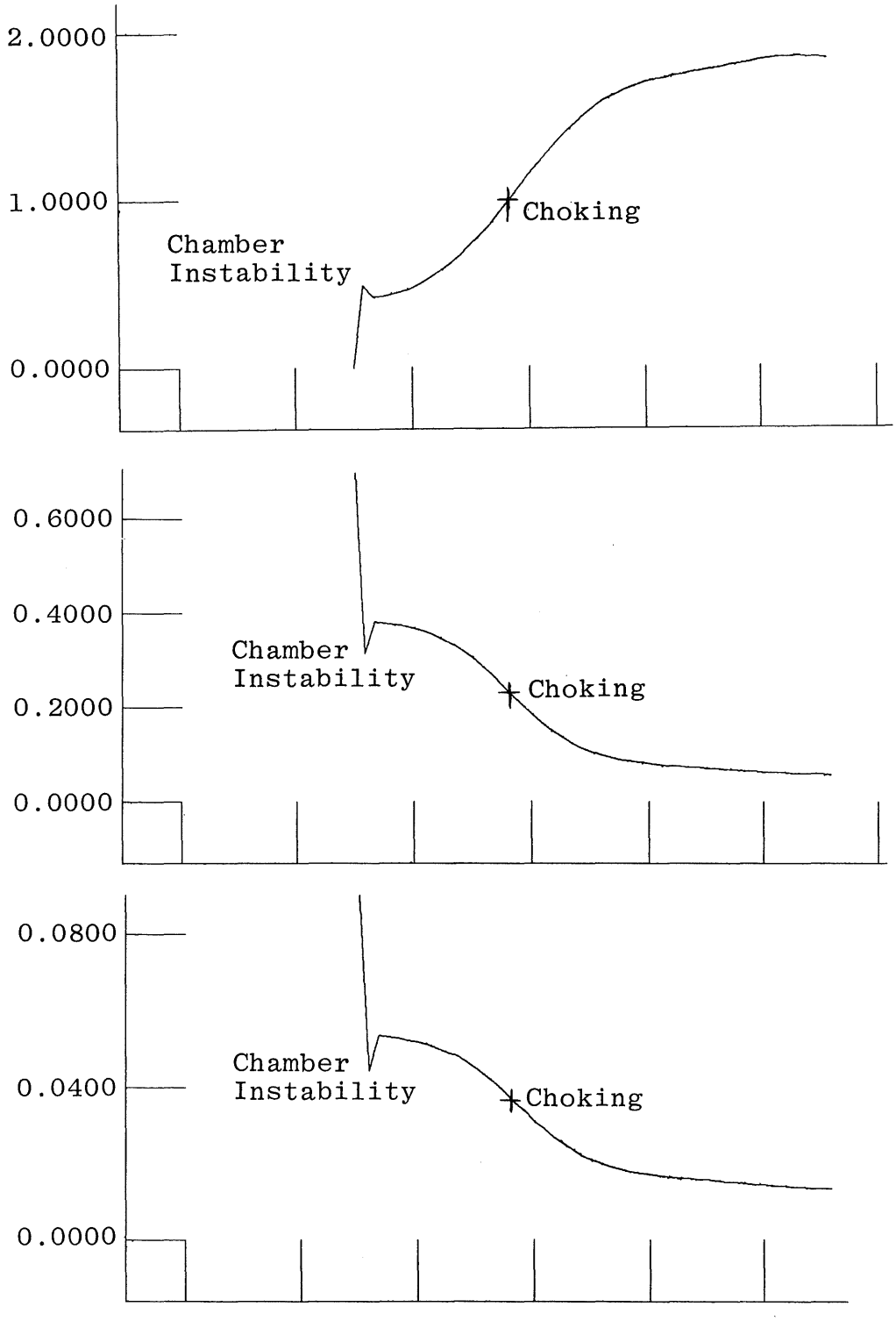


Figure 30 (Continued)

Initially, the chamber pressure is so low that separation occurs (Figures (31) and (32)). The chamber pressure was then increased in order to generate a normal shock in the nozzle. As the chamber pressure is increased further, the stationary position of the shock moves toward the aft end of the nozzle. The Rankine-Hugoniot equations were again obeyed.

Re-entry Vehicle (RV)

A re-entry vehicle was examined under inviscid and viscous conditions at hypersonic speeds (M = 22). Figures (33) and (34) illustrate the bow shock and region of undisturbed flow for both the inviscid and viscous cases. In the latter case, the influence of viscosity is seen in the development of a laminar boundary layer on the surface and a vortex being formed in the rear of the RV.

M-117 Warhead

The aerodynamic characteristics of an M-117 warhead were examined under subsonic, transonic and supersonic inviscid conditions. Four free stream Mach conditions were studied: $M_\infty = 0.5$, $M_\infty = 0.88$, $M_\infty = 1.14$ and $M_\infty = 1.80$. Figures (35) through (37) represent contours for the four cases stated above. Figures (38) and (39) illustrate the pressure coefficients for the subsonic and transonic cases and results are compared with experiment.

3.4 Diffusion

The time dependent diffusion equation for heat conduction (energy equation), magnetic diffusion (induction equation) and viscous transport (momentum equation) was solved.

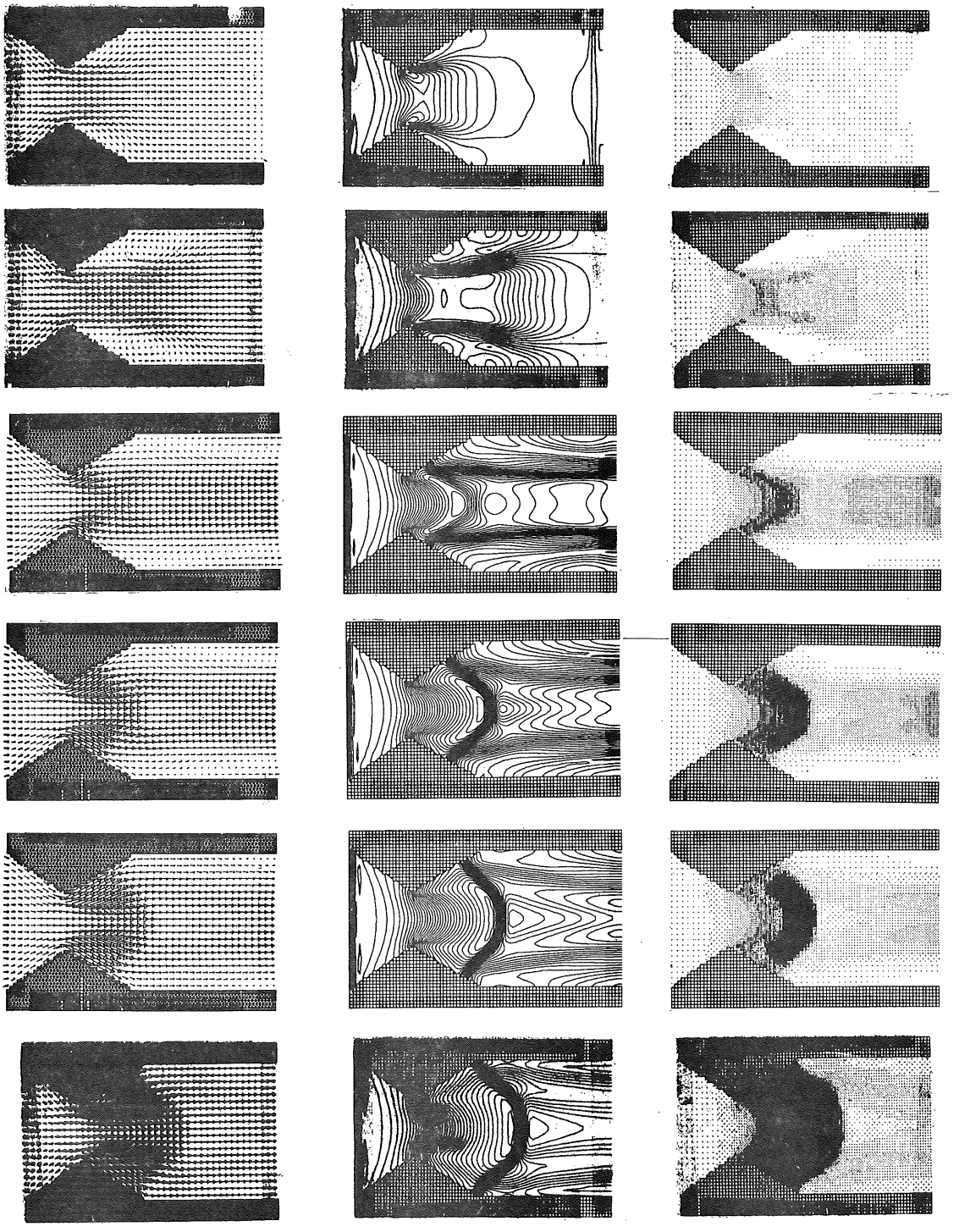


Fig. 31 Transient Nozzle Flow, Separation and Shock Formation

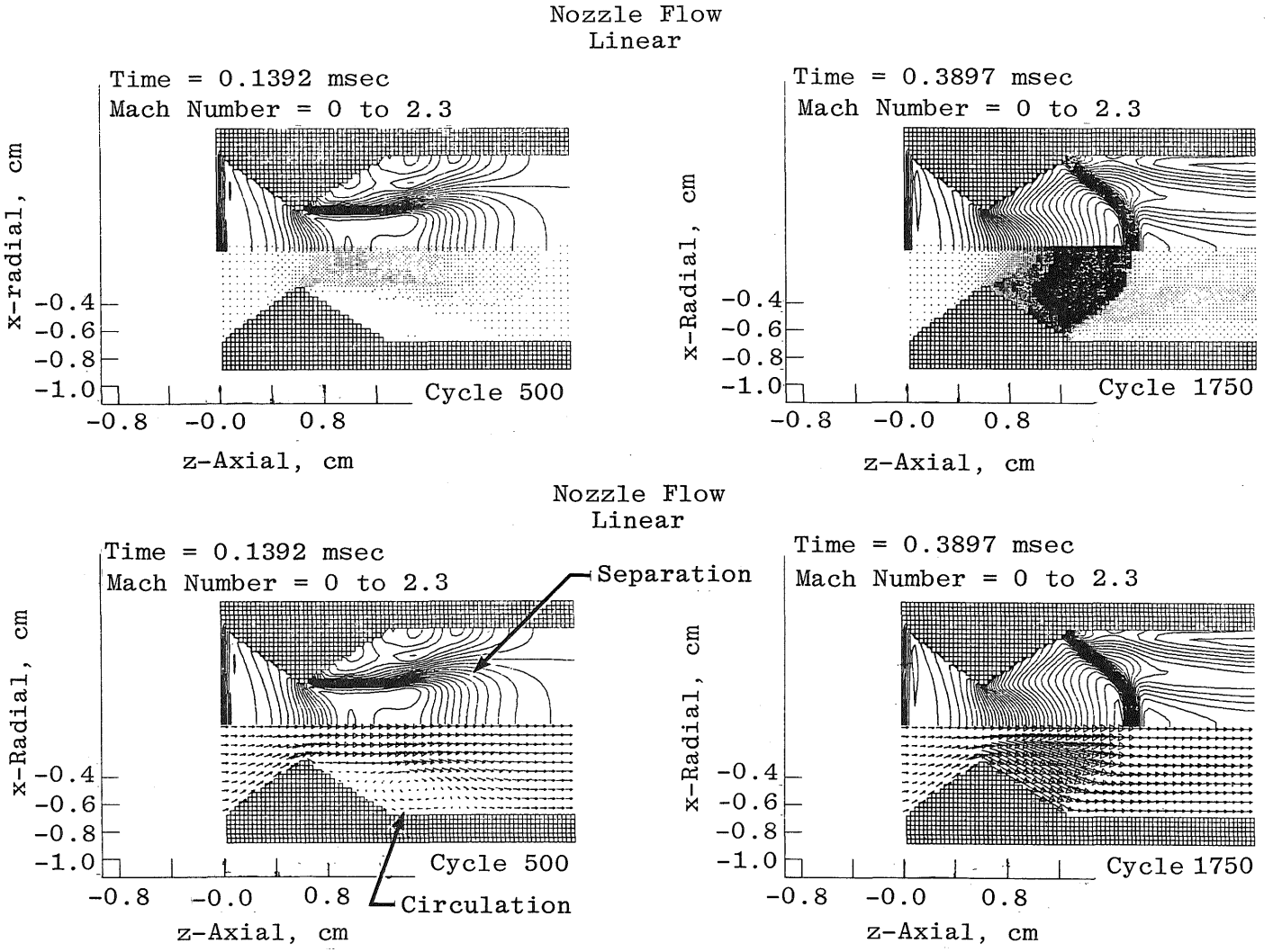


Fig. 32 Nozzle Separation and Shock Formation. Mach Contours and Mach Shading (Above) and Mach Contours and Velocity Vectors (Below)

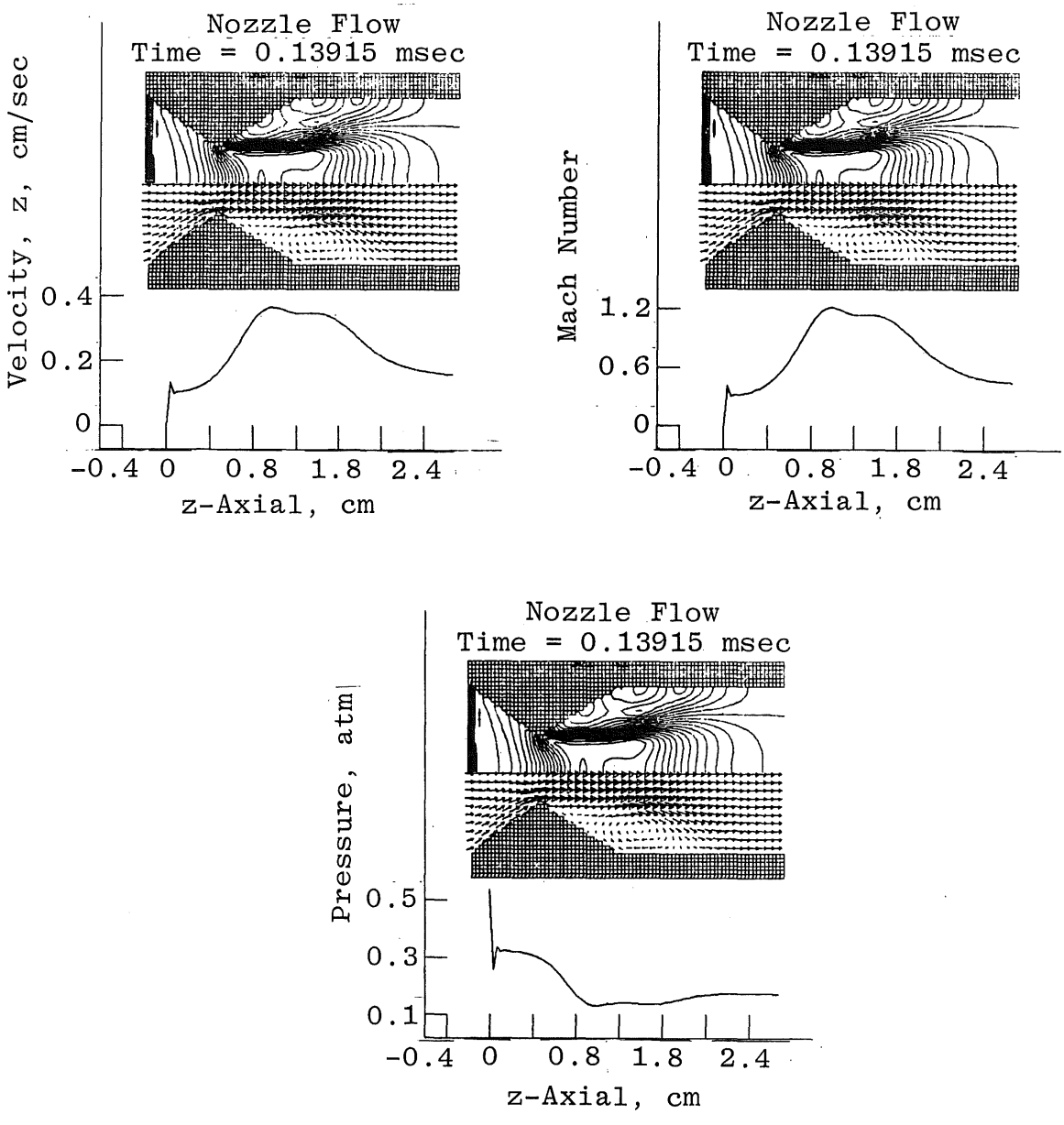


Figure 32 (Continued)

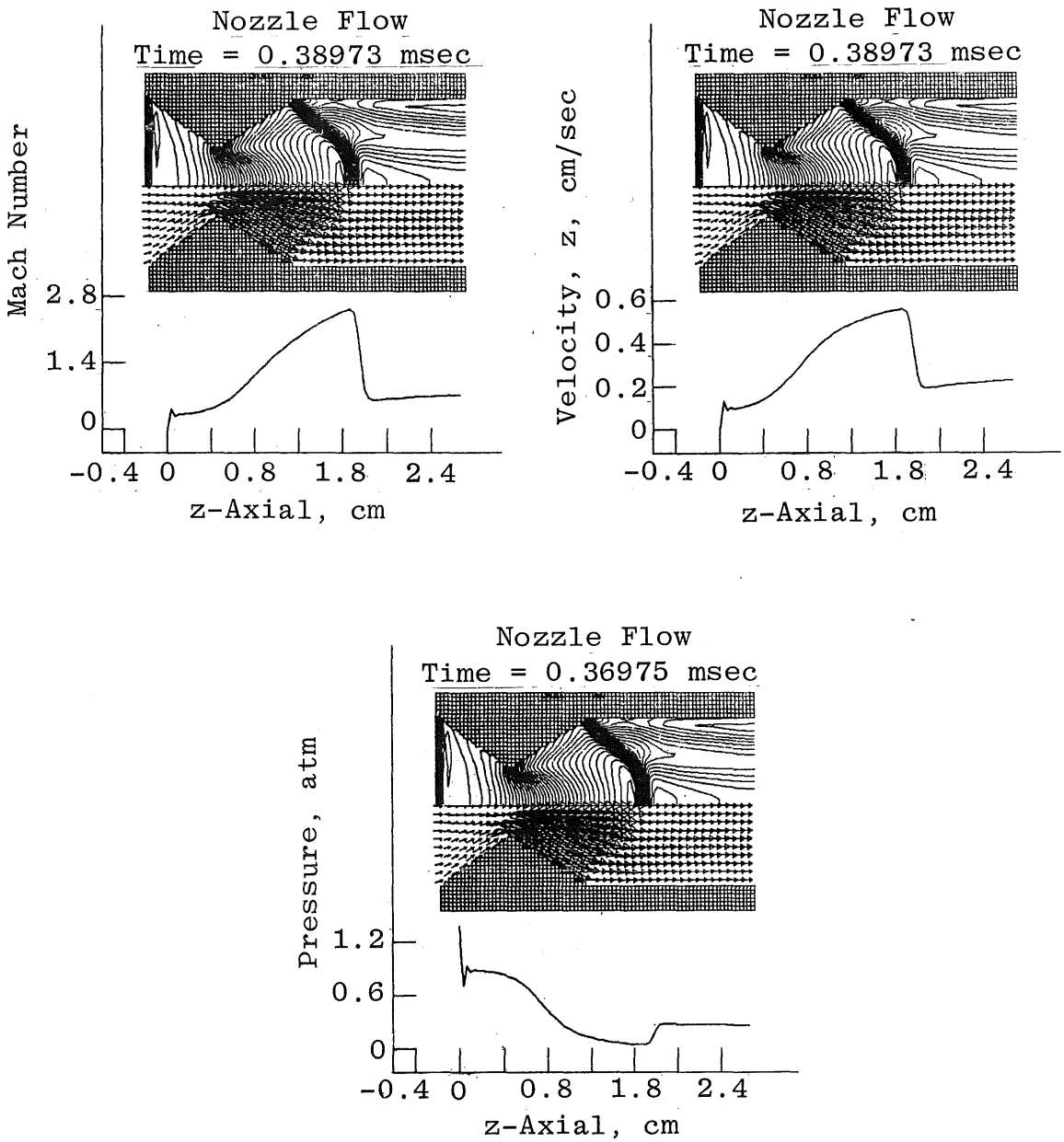


Fig. 32 (Continued)

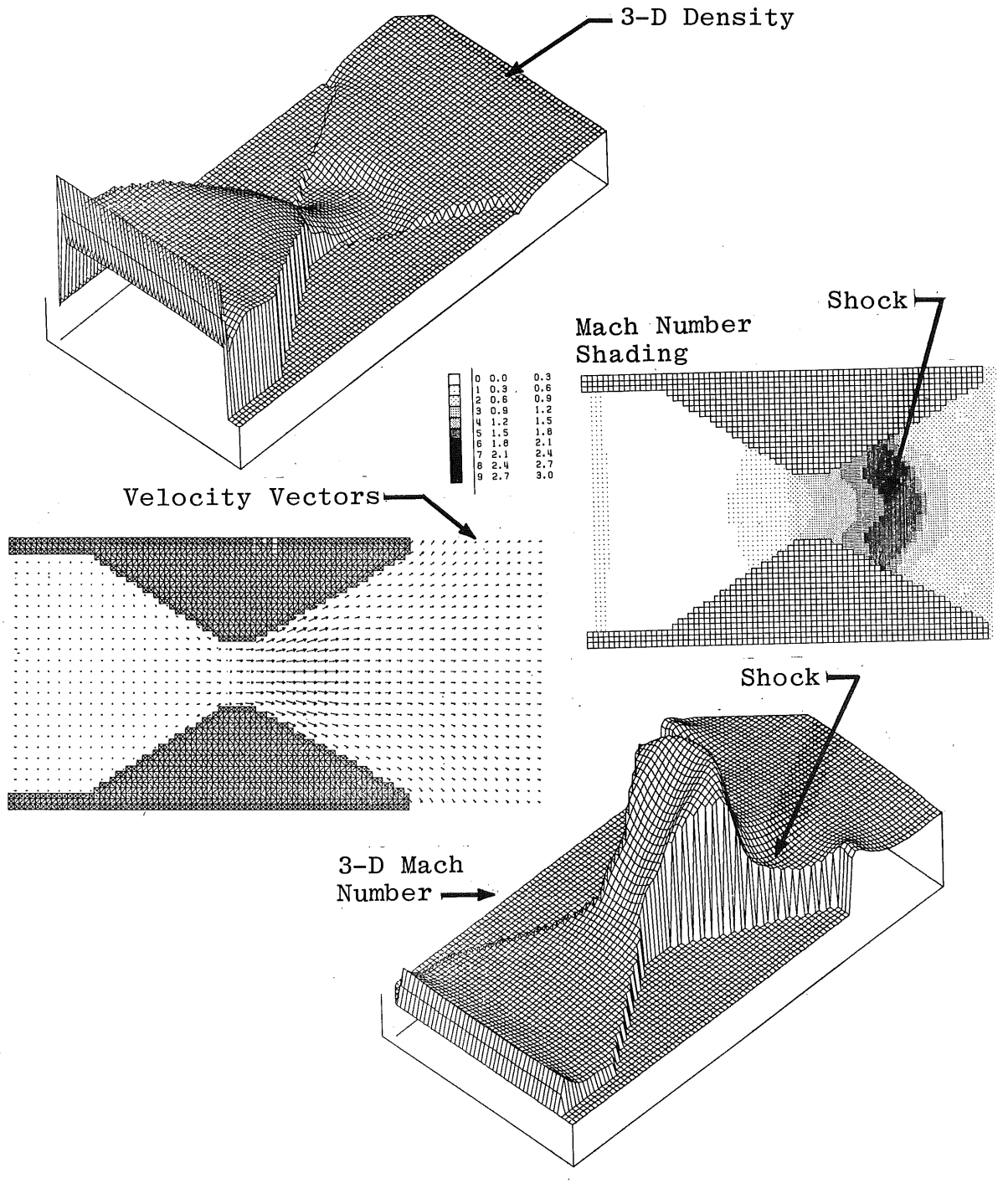


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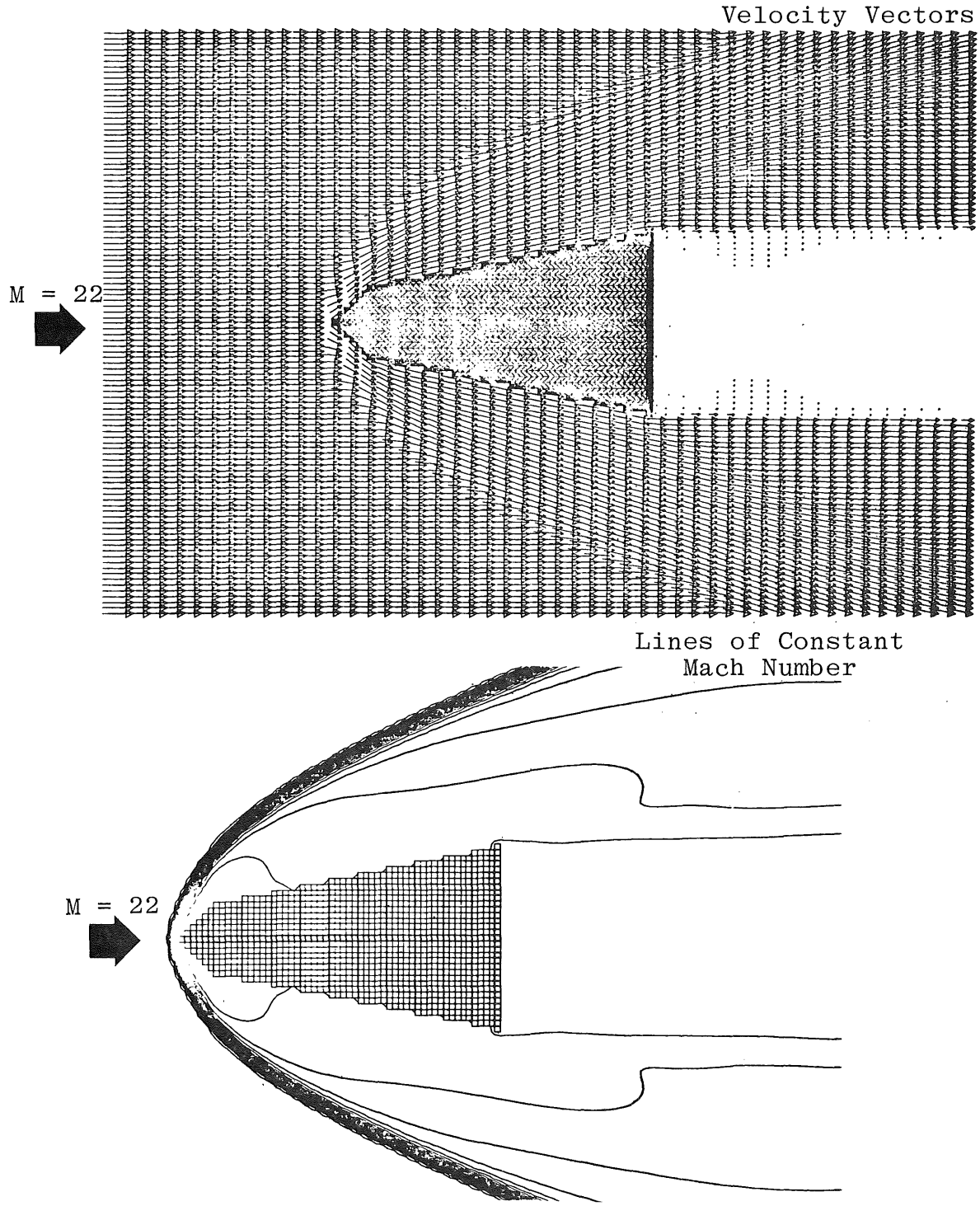


Fig. 33 Re-Entry Vehicle Inviscid Solutions

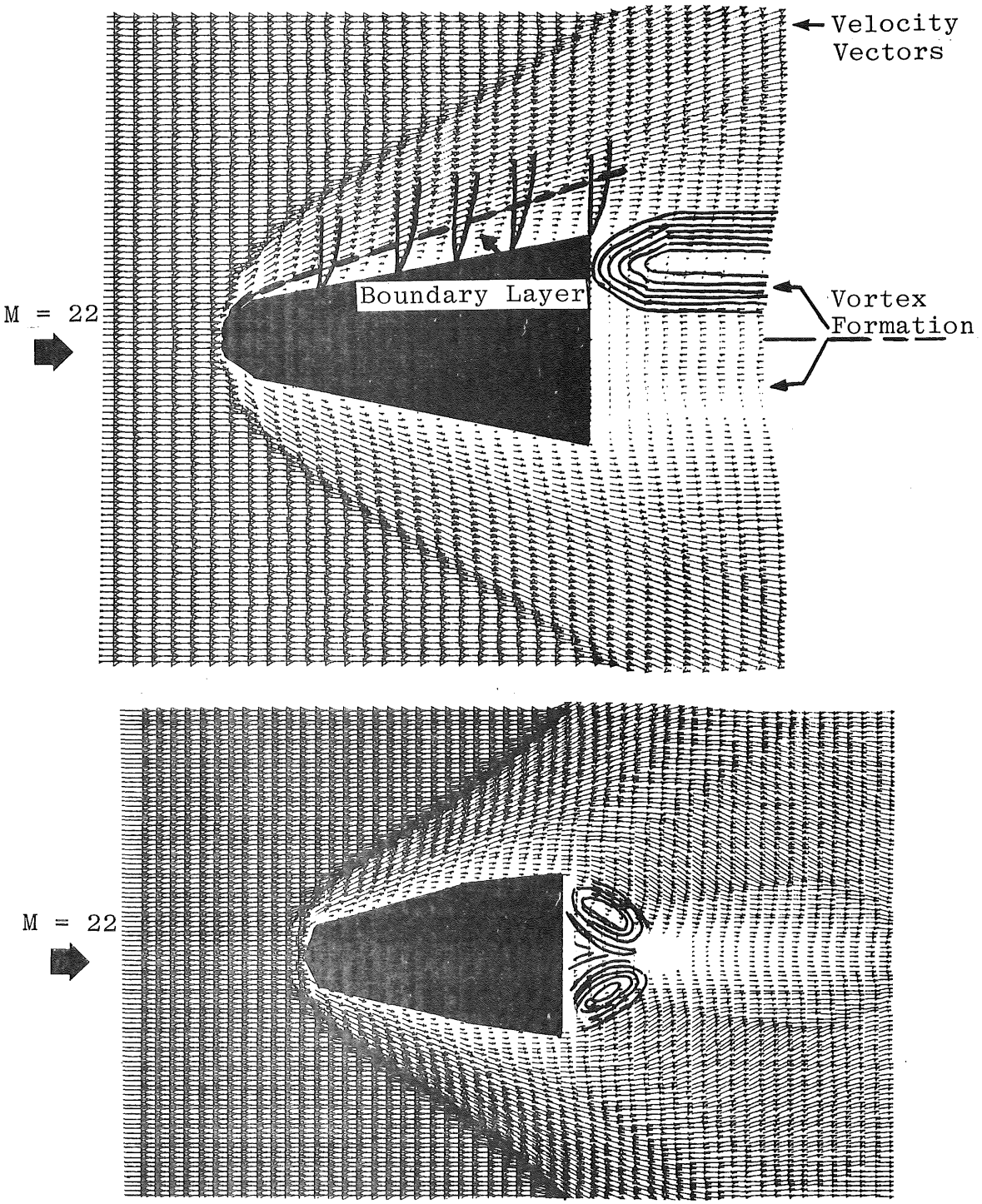


Fig. 34 Re-Entry Viscous Solutions

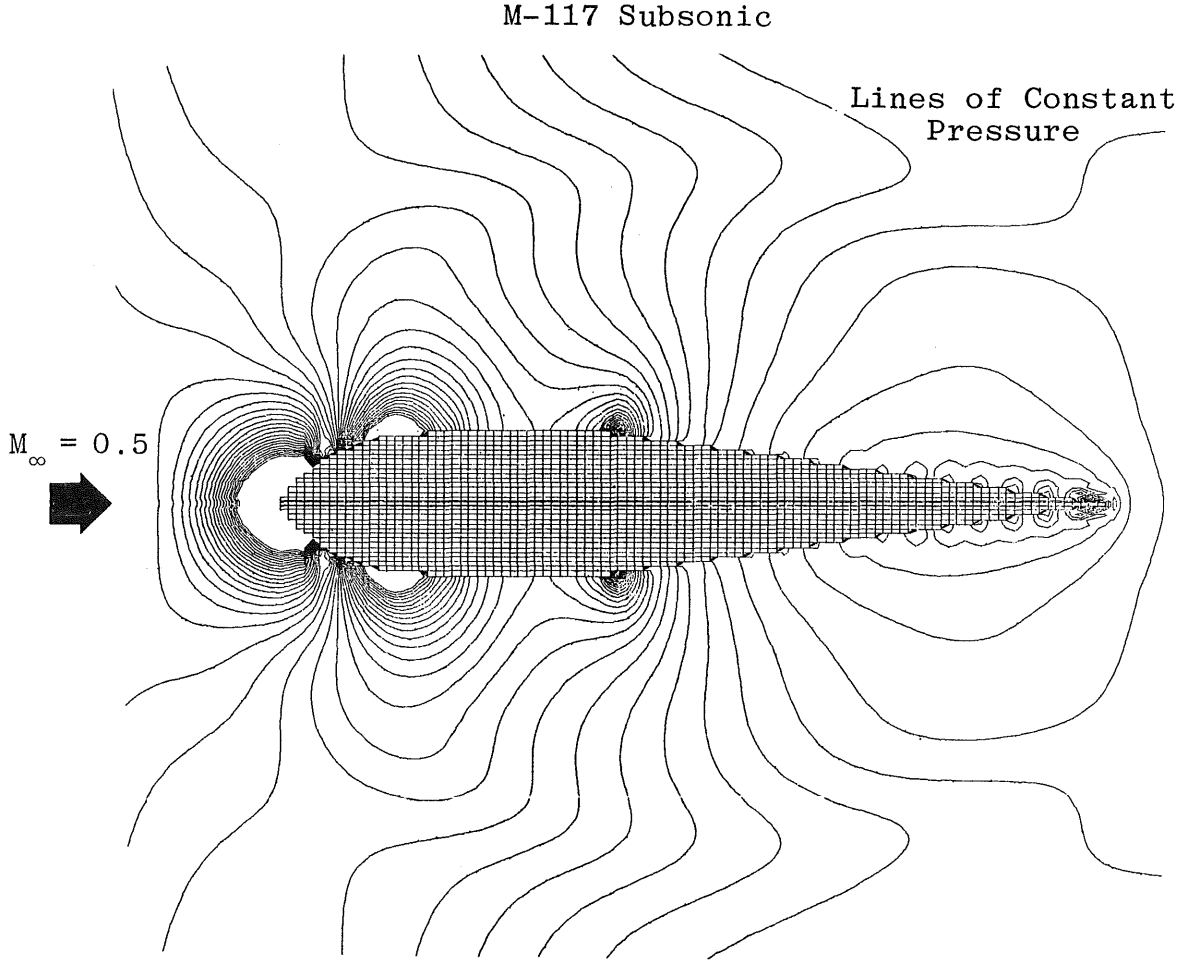


Fig. 35 M-117 Pressure Contours, M_∞ = 0.5

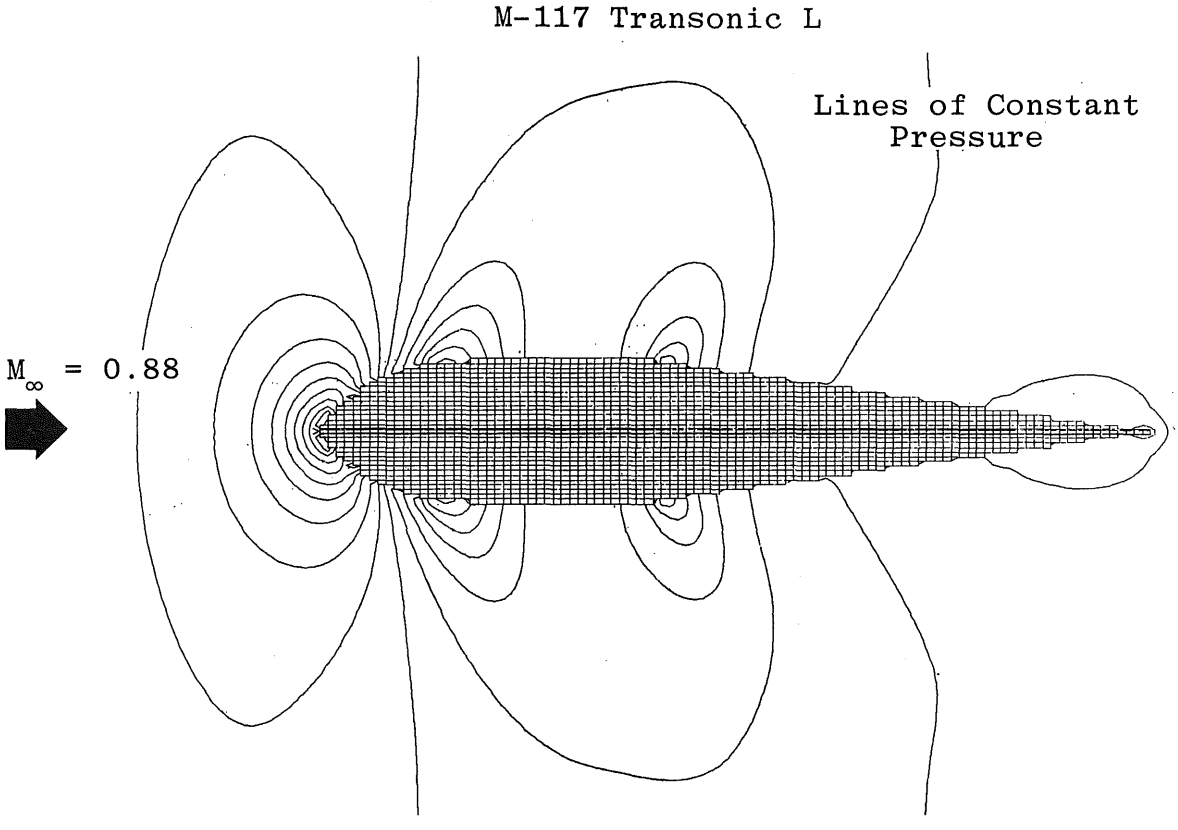


Fig. 36 M-117 Pressure Contours, M_∞ = 0.88

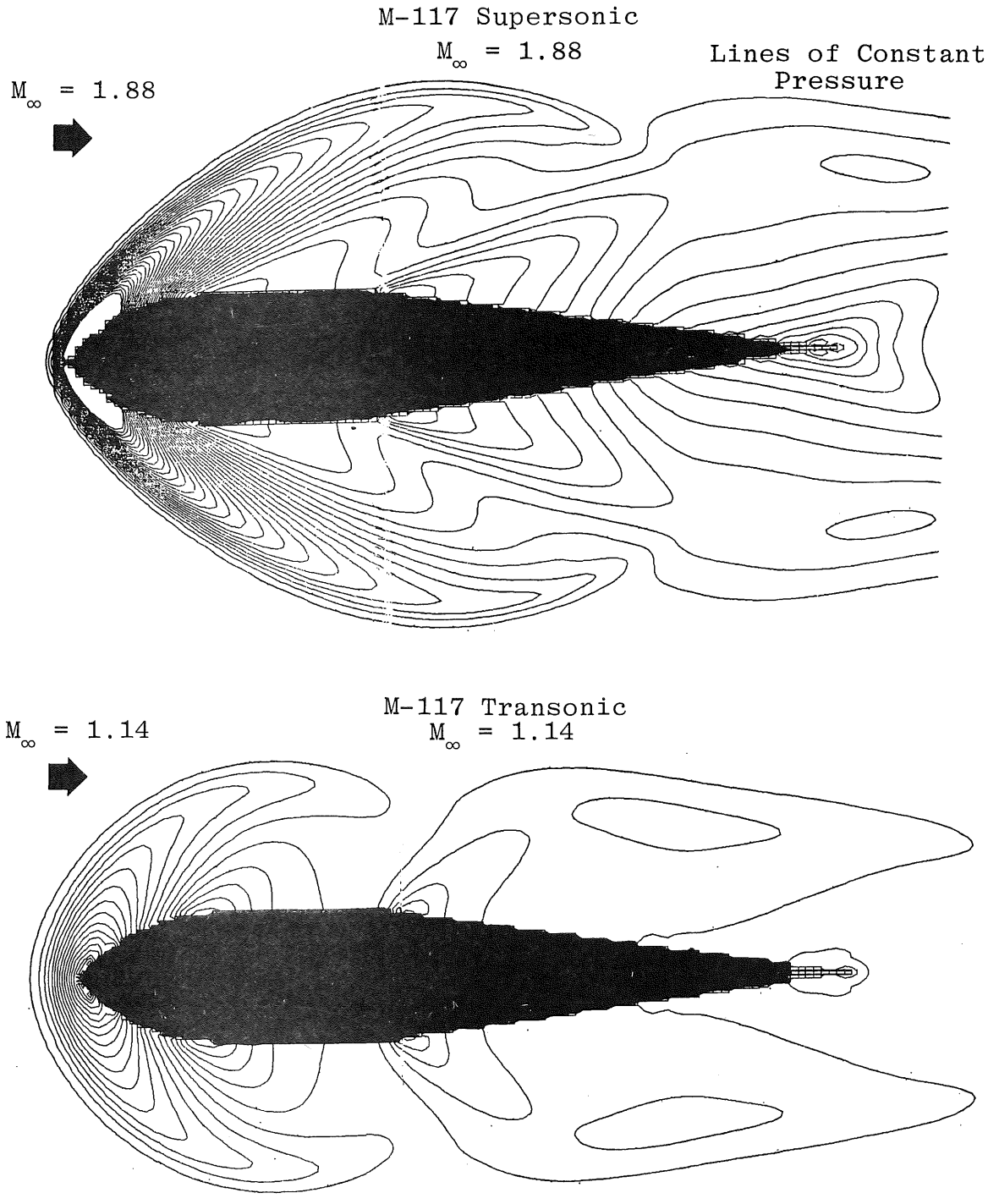


Fig. 37 M-117 Pressure Contours, M_∞ = 1.14 and M_∞ = 1.88

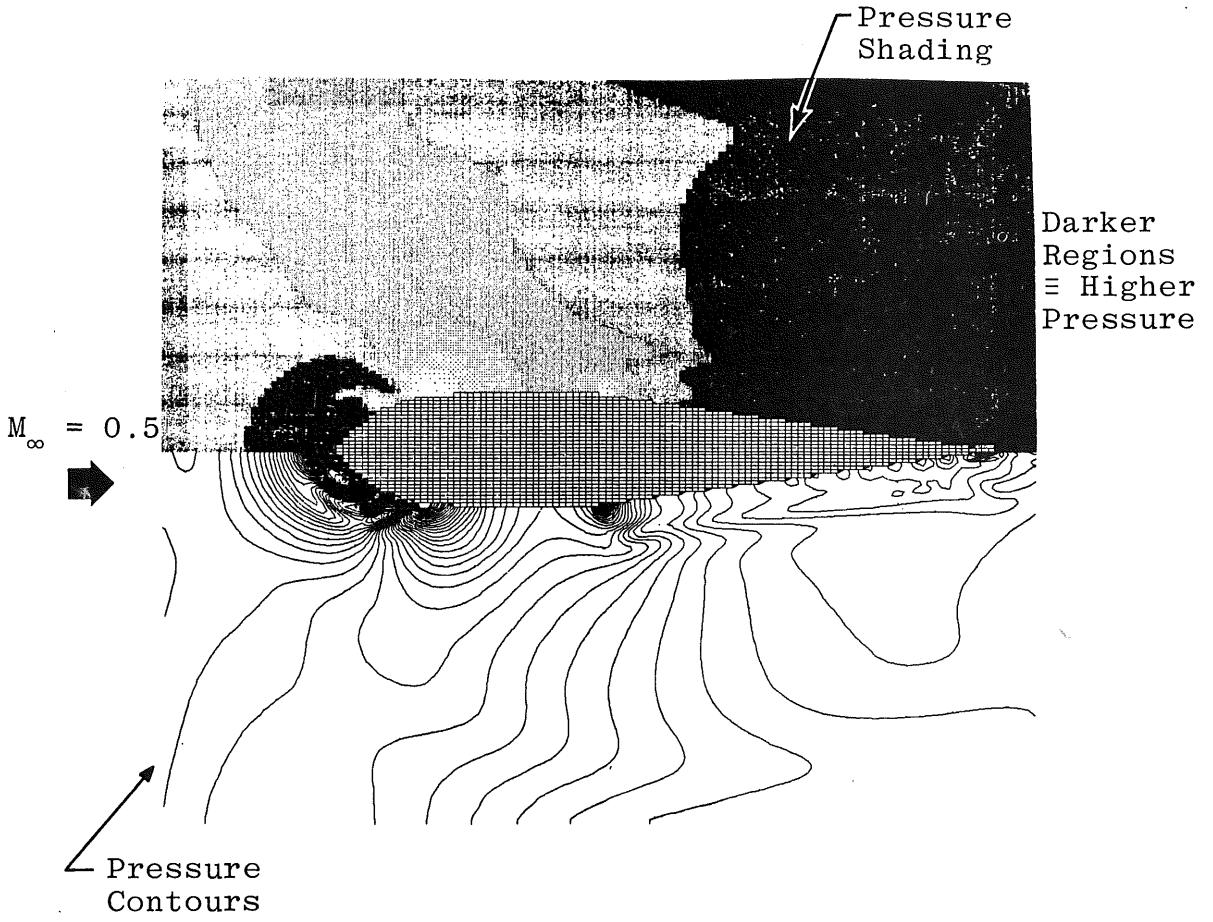


Fig. 37 (Continued)

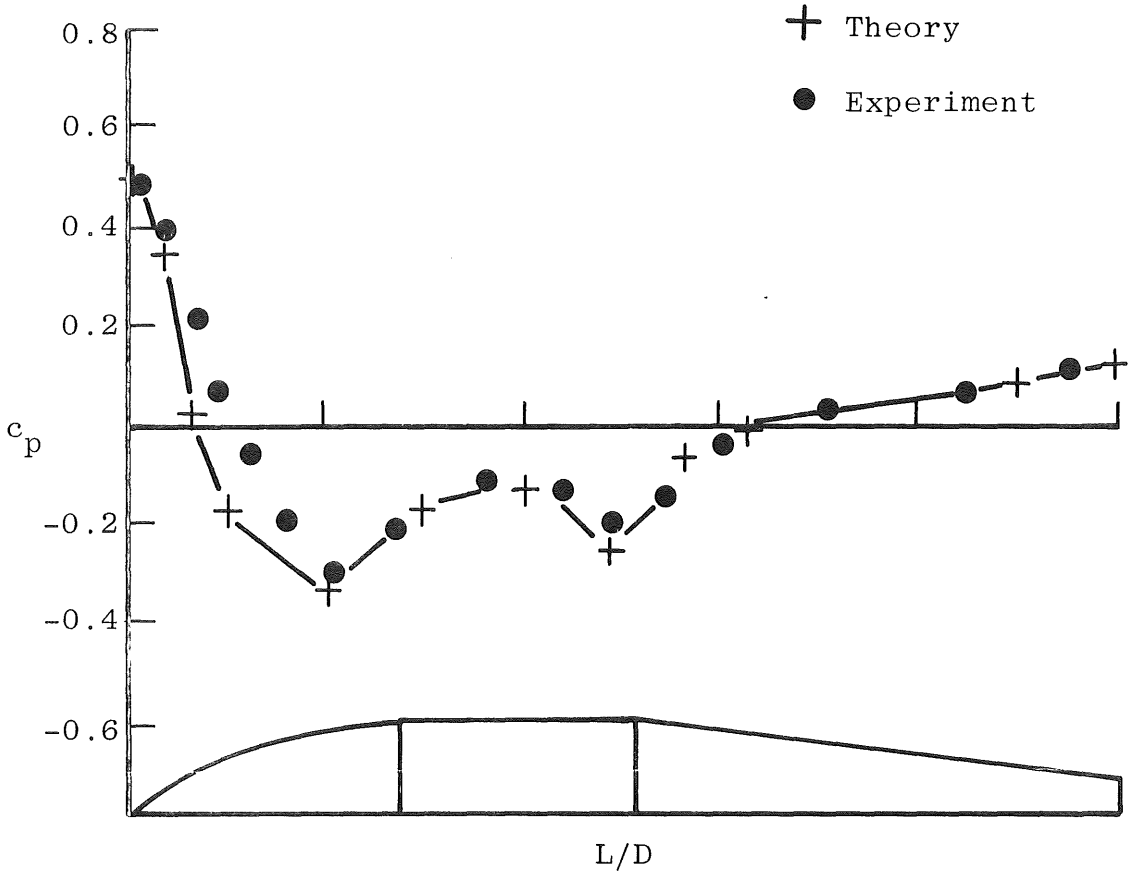


Fig. 38 M-117 Pressure Coefficient, M_∞ = 0.5

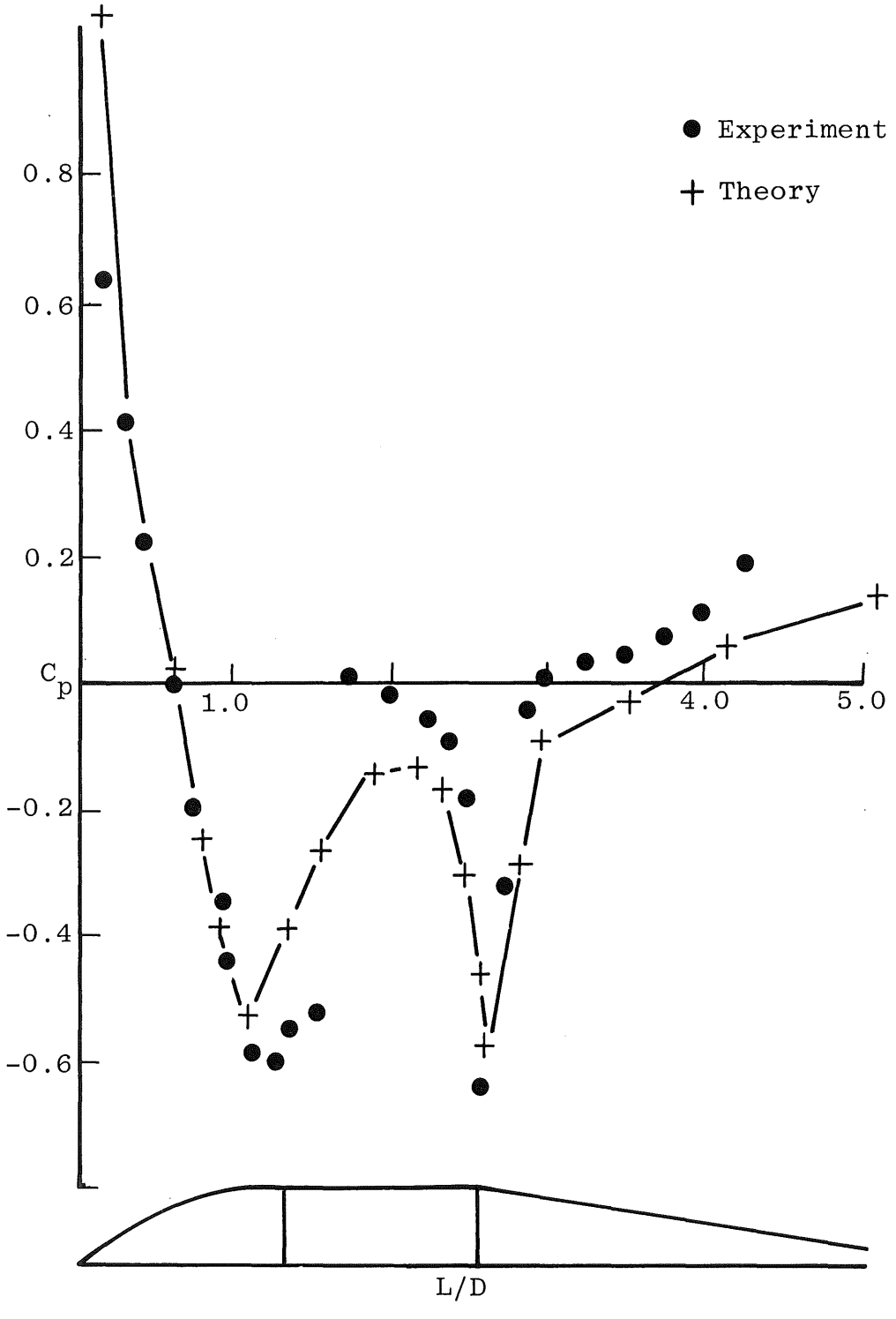


Fig. 39 M-117 Pressure Coefficient, M_∞ = 0.88

Examining the momentum, energy and induction equations and eliminating all convective ($\bar{v}\cdot\nabla$) and hydrodynamic (∇p) effects, the one-dimensional equations reduce to:

$$\frac{\delta}{\delta t}(u) = \frac{1}{\rho}\frac{\delta}{\delta r}\left(\frac{\delta}{\delta r}(u)\right) \tag{211}$$

$$\frac{\delta}{\delta t}(T) = \frac{1}{\rho C_v}\frac{\delta}{\delta z}\left(\lambda\frac{\delta}{\delta z}(T)\right) \tag{212}$$

$$\frac{\delta}{\delta t}(B_\theta) = \frac{\delta}{\delta z}\left(\frac{1}{\sigma\mu_p}\frac{\delta}{\delta z}(B_\theta)\right) \tag{213}$$

Allowing for the diffusivities to be constant and equal to one:

$$\frac{\mu}{\rho} = 1 \; ; \; \frac{\lambda}{\rho C_v} = 1 \; ; \; \frac{1}{\sigma\mu_p} = 1 \tag{214}$$

Equations (211), (212) and (213) become identical and result in similar solutions for the same initial and boundary conditions.

For example, given a body, initially at an internal temperature of 100°K and an external (environmental) temperature of 200°K as shown in Figure (40) it is desired to find the increase in internal temperature as a function of time. A closed form analytic solution to Equations (211) through (214) has been obtained for the time dependent problems posed above. In all cases, the transient solution agreed with the analytic results to any desired accuracy by refining the mesh and time step. Figure (40) and Table (5) illustrate the compatibility between the numerical results and the analytic solution. Identical results were obtained by solving the momentum and induction equations with analogous boundary conditions.

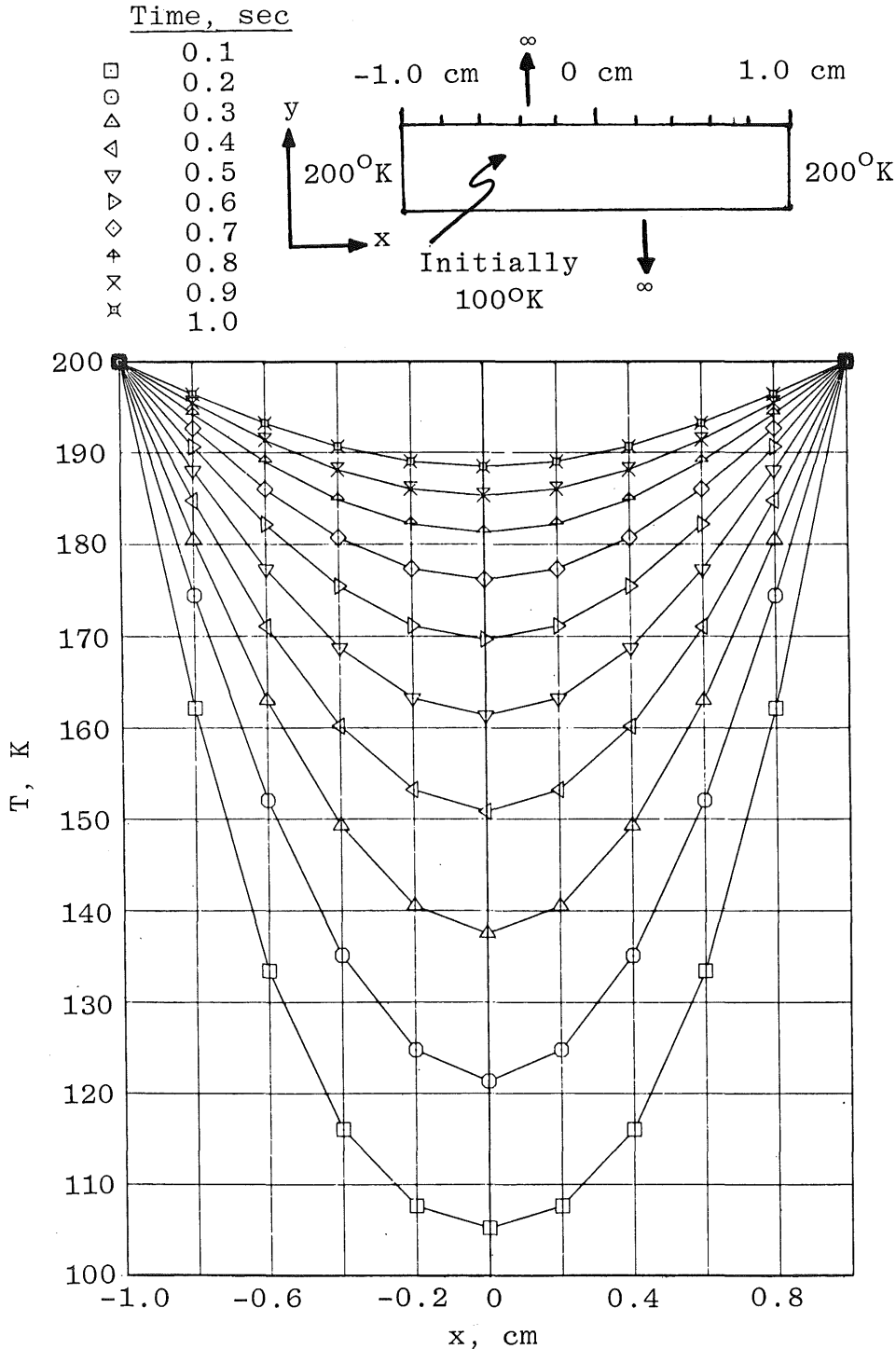


Fig. 40 Transient Thermal Diffusion

Table (5) Comparison between Numerical and Analytic Solutions for the Diffusion Equation.

	CENTERLINE RESULTS			
	NUMERICAL		ANALYTIC	
TIME sec	U or T or B cm/sec °K gauss		U or T or B cm/sec °K gauss	
0.0	100.0		100.0	
0.1	103.8		105.0	
0.2	121.6		122.0	
0.3	138.5		139.5	
0.4	152.0		152.0	
0.5	162.5		162.5	
0.6	170.7		170.5	
0.7	177.2		177.0	
0.8	182.2		182.0	
0.9	186.1		186.0	
1.0	189.1		189.0	

Finally, a pressure pulse was generated by disturbing the left boundary and allowing the sound wave to propagate to the right boundary, reflect, and return to the point of creation. Figure (41) illustrates this wave configuration moving at sound speed = $(\gamma P/\rho)^{\frac{1}{2}}$ or approximately 30,000 cm/sec.

3.5 Electric and Magnetic Fields

Solution to the equations of motion for a conducting fluid requires that the current and the magnetic and electric fields be known at every position within the fluid. As discussed in Section (2), for high magnetic Reynolds numbers, the current and electromagnetic fields are computed based on the magnetic induction equation and Ohm's Law. For flow with low magnetic Reynolds number, an electric potential or current stream function is used to calculate the electric field and current

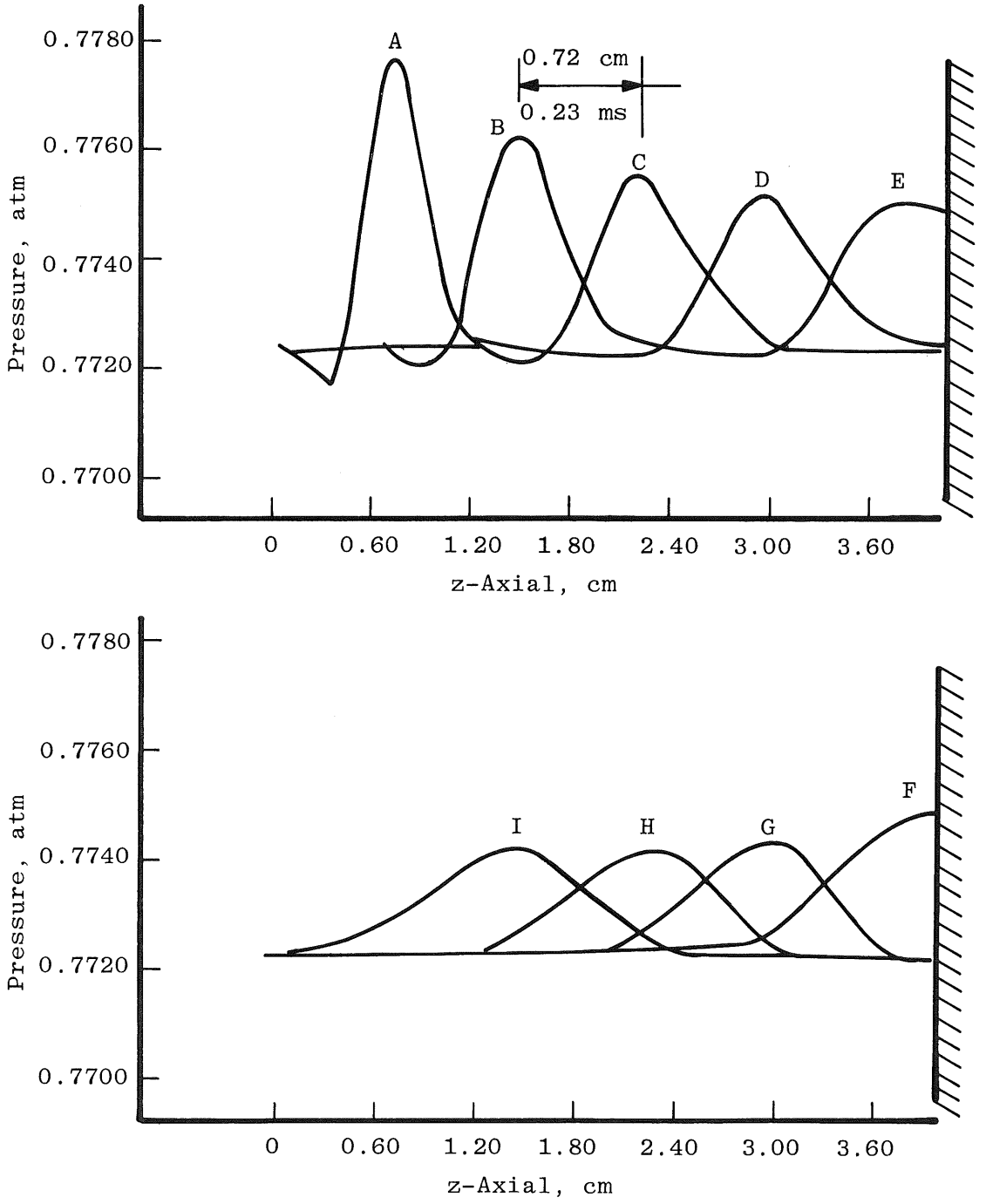


Fig. 41 Propagating Sound Wave

distribution where the induced magnetic field is considered negligible by virtue of its low magnetic Reynolds number.

Employing the finite difference equations and boundary conditions discussed in Section (2), several simple low magnetic Reynolds number problems were solved using the current stream function defined by Equation (65). Considering one electrode-pair with no Hall current, a solution to Equation (53) was attained, using the method of Successive Over-Relaxation. Based on this solution,the current vectors, the current stream function, the electric potential, were calculated and are shown in Figures (42) to (45). A calculation was performed for Hall Parameter = 5 with results shown in Figure (46). Figure (47) depicts the convergence of the current stream function. Finally, three electrode-pairs (β = 2) were analyzed in the same manner and results are graphically displayed in Figures (48) and (49).

Figures (50) through (53) show the transient current stream lines when a shock wave is passing through the single electrode-pair channel. As the shock enters the channel, an electric field is induced since the EMF ahead and behind the shock wave are different. Eddy currents are set up resulting from this electric field. However, the boundary conditions of the current stream function at the channel exit (and entrance) requires a uniform Ψ across the duct. In order to satisfy this boundary condition, a secondary current eddy is set up opposite the principal eddy induced by the shock wave. Figure (42) shows the undisturbed current streamlines and Figures (50) through (53) represent

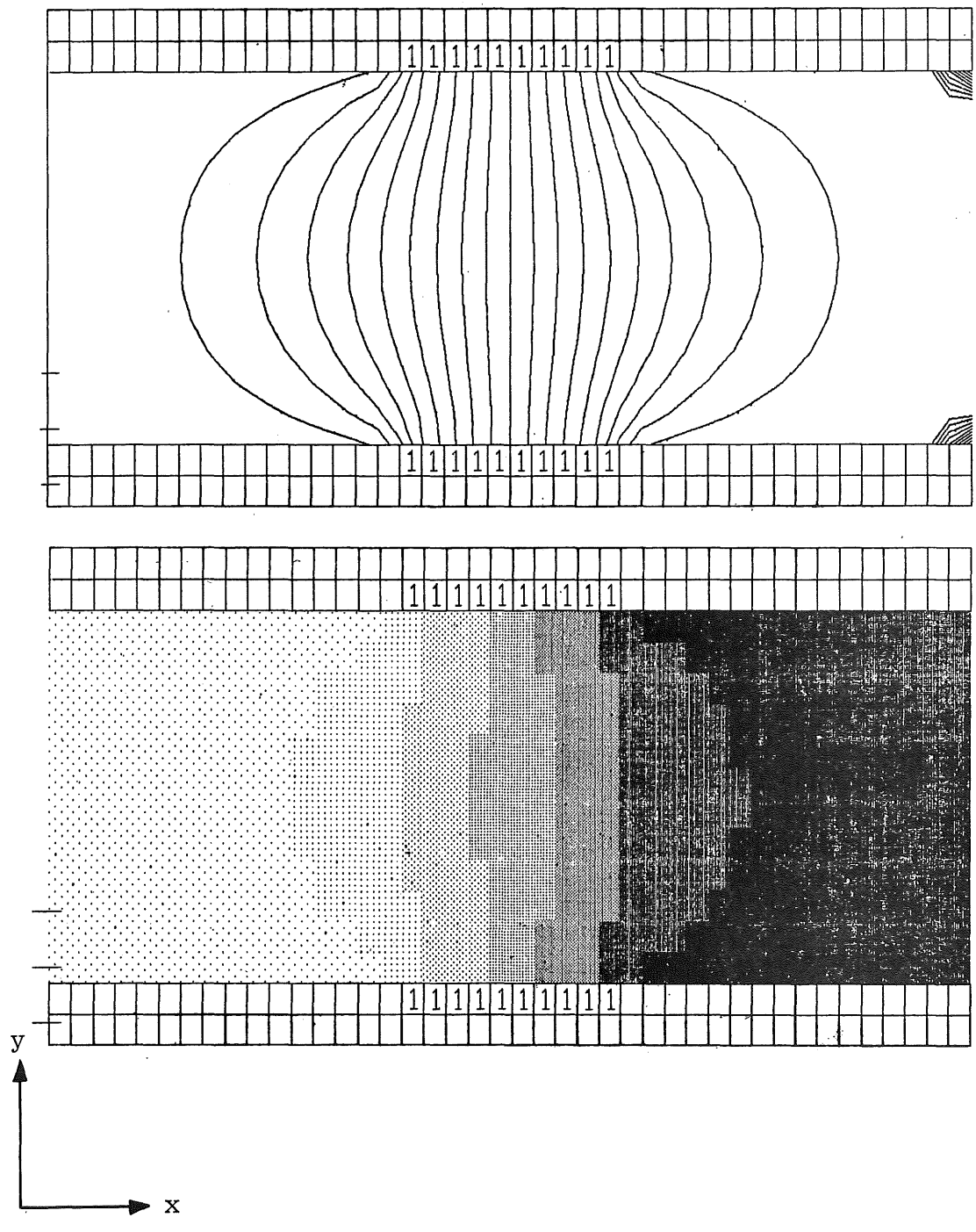


Fig. 42 One-Electrode Pair. Current Stream Function Contour and Shading Plots

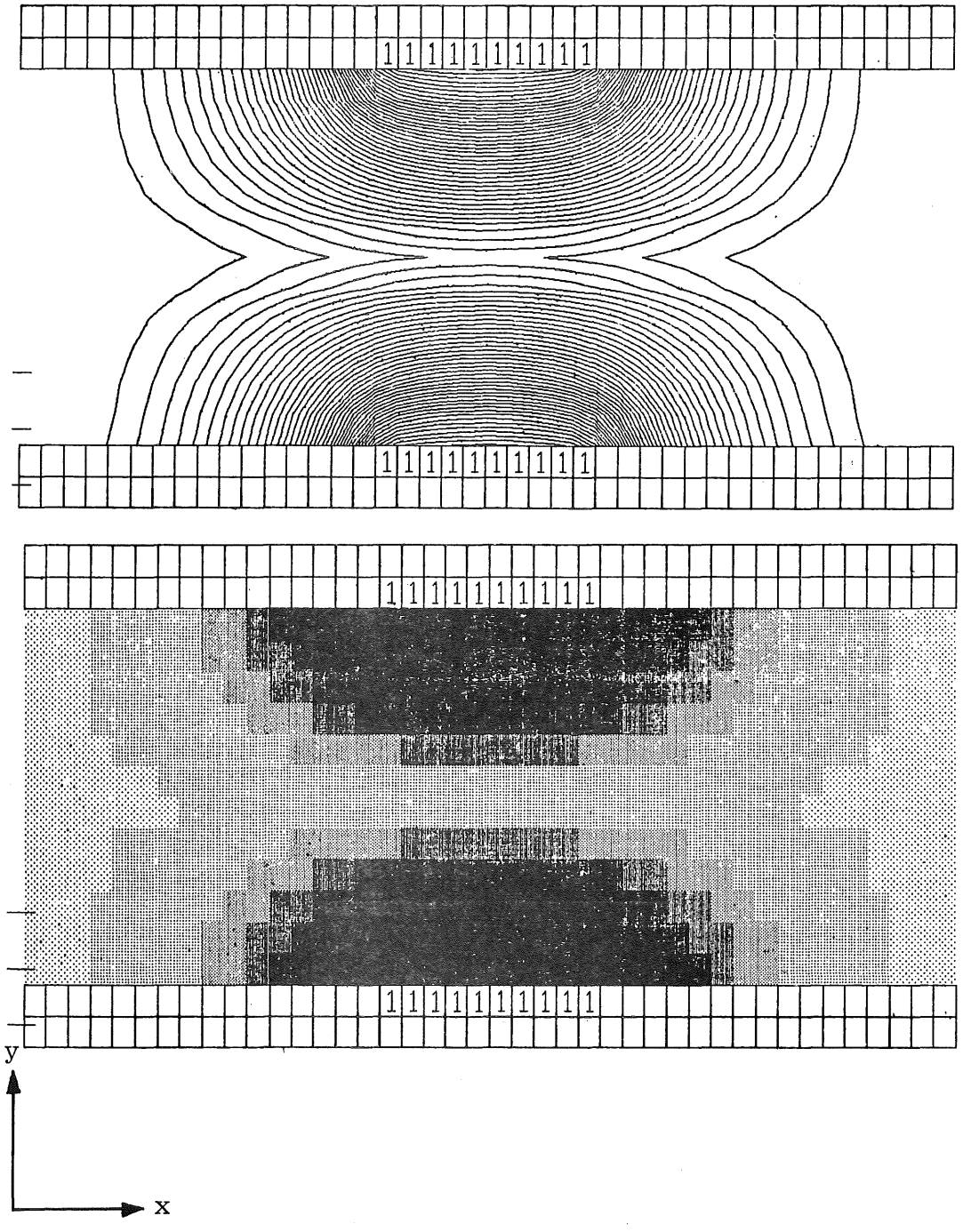


Fig. 43 One-Electrode Pair. Electric Potential Contours and Shading Plots

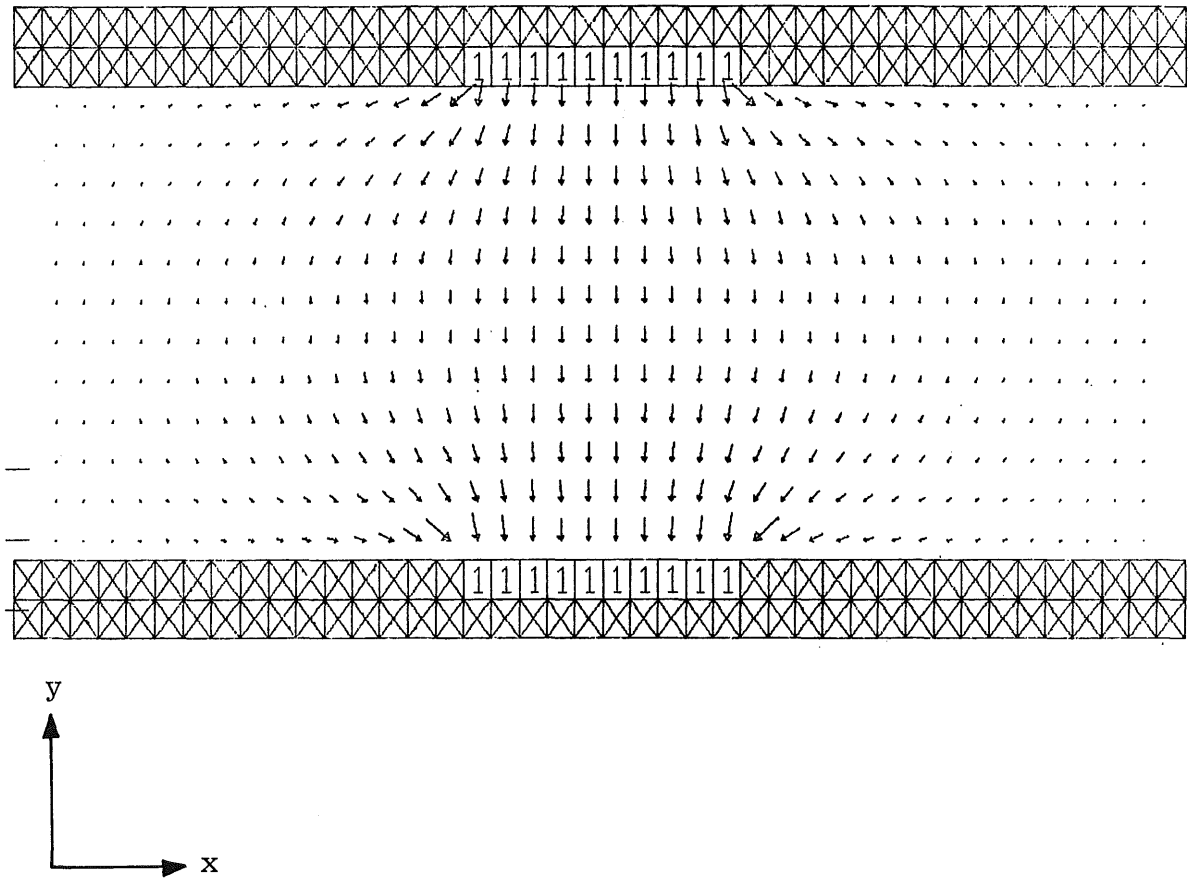


Fig. 44 One Electrode-Pair. Current Vectors.

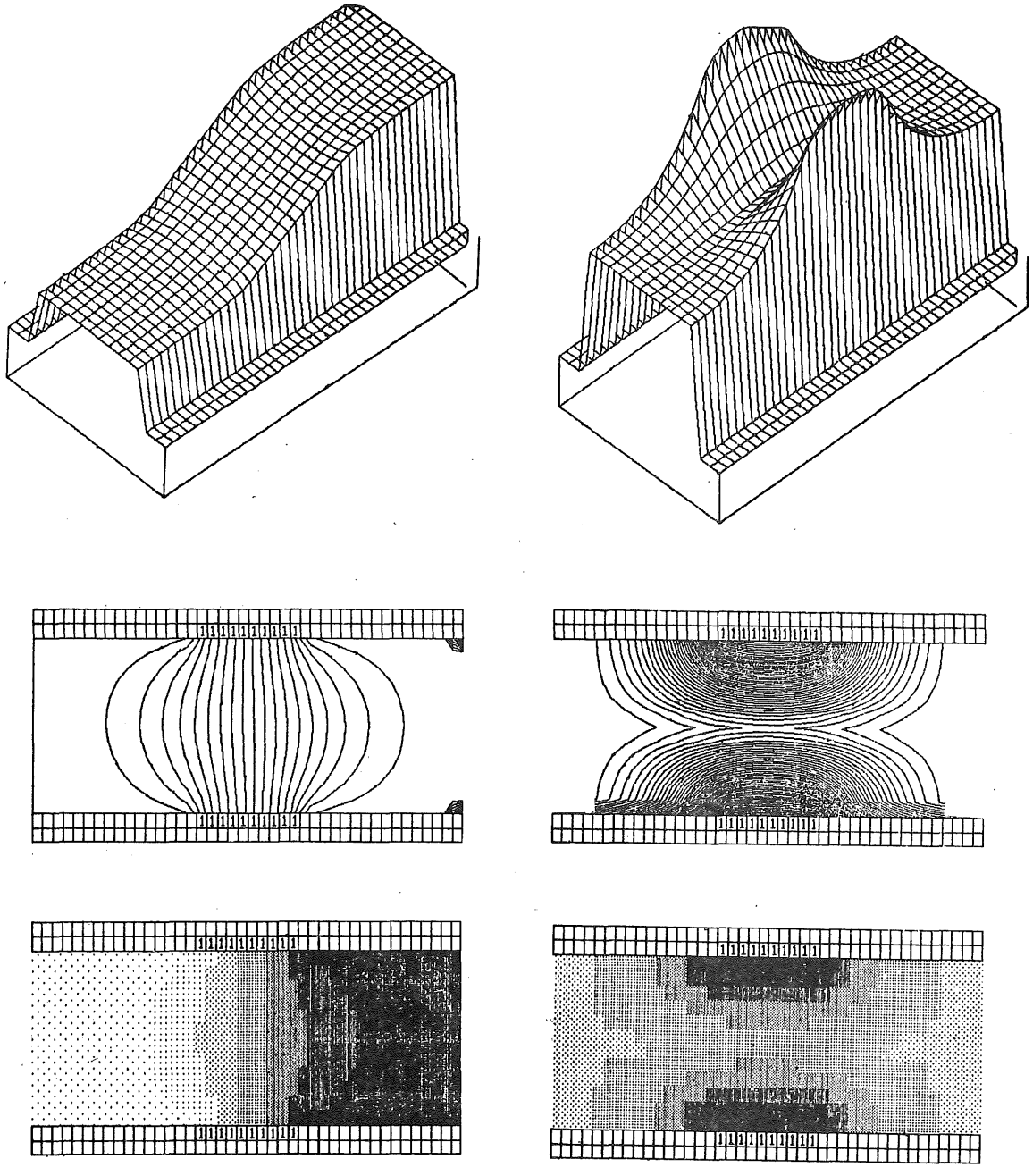


Fig. 45 One-Electrode Pair, 3-D Plots. Current Stream Function and Electric Potential

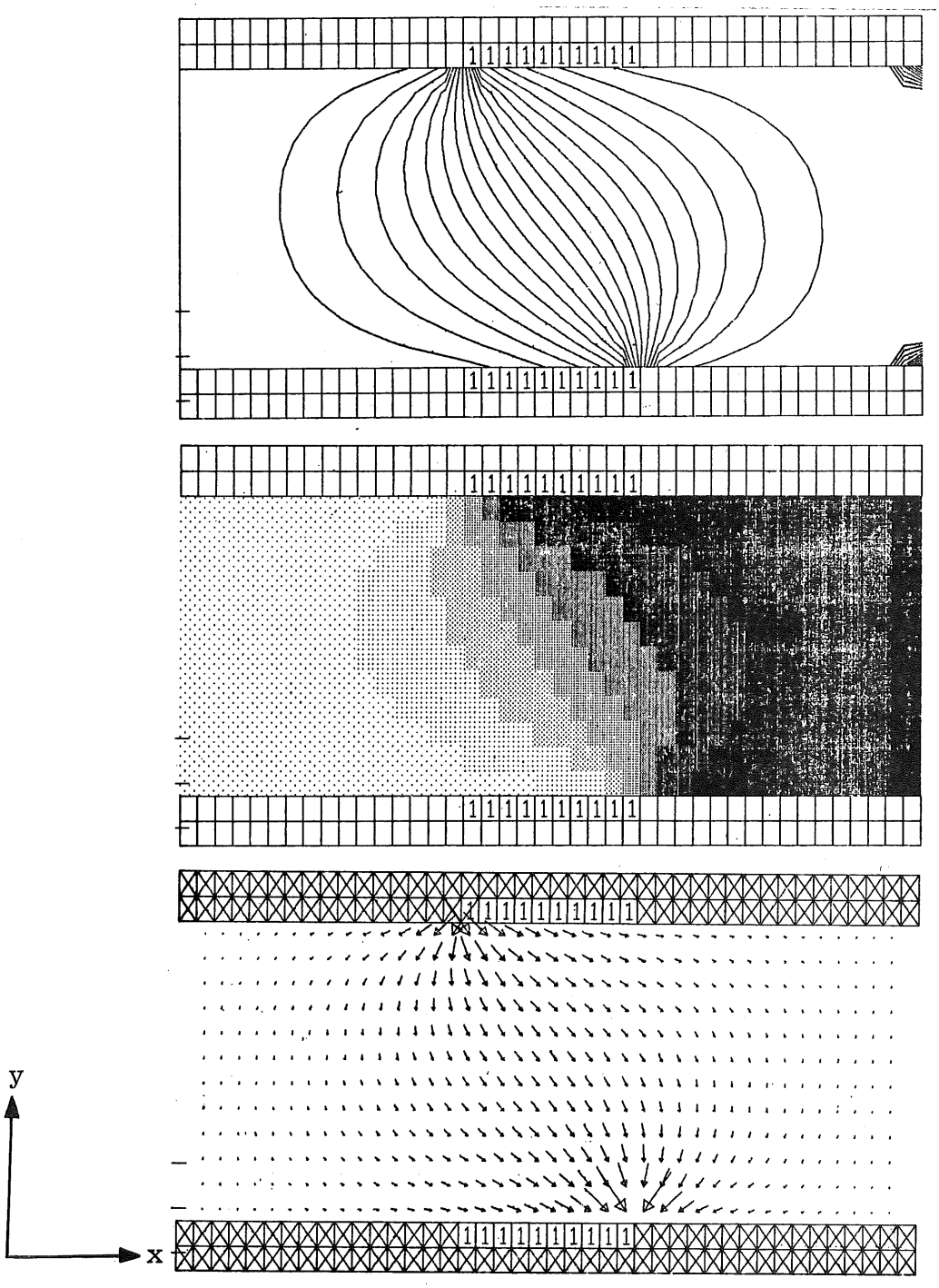


Fig. 46 One-Electrode Pair (β = 5). Current Stream Function and Current Vectors

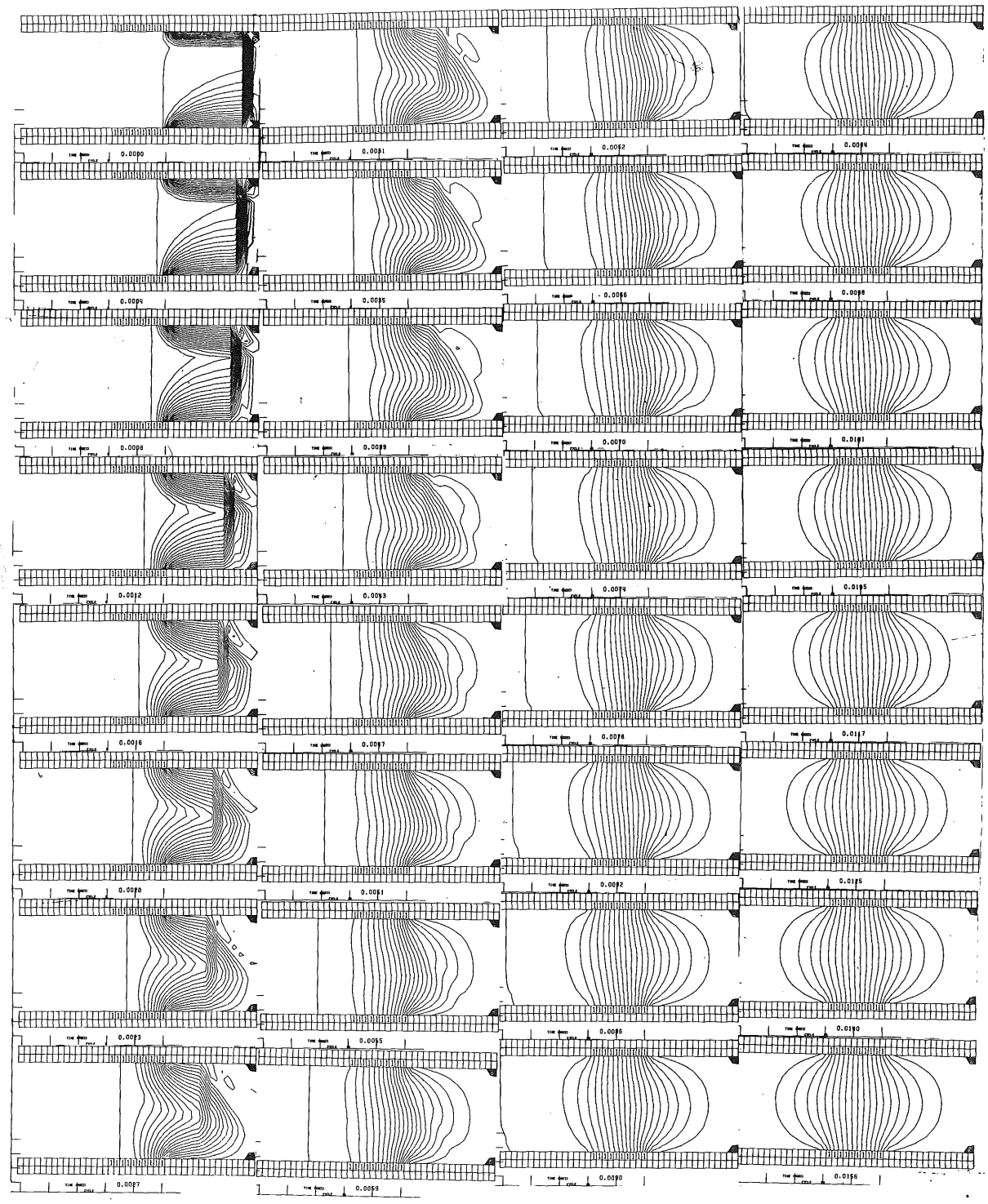
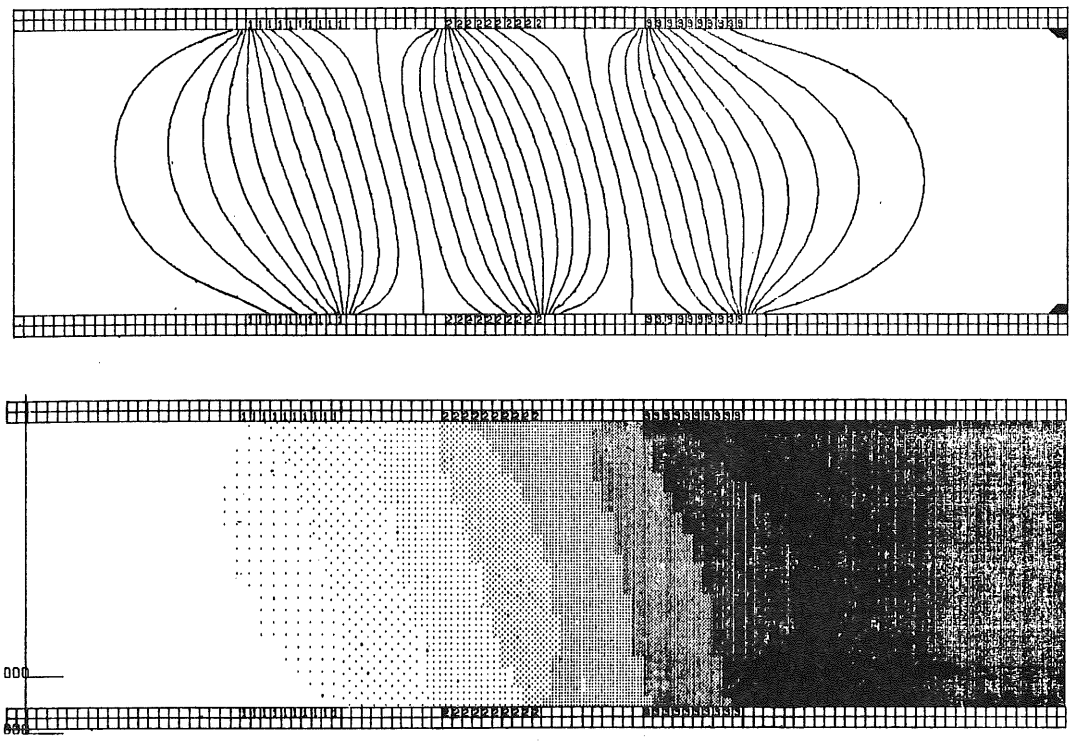


Figure 47 One-Electrode-Pair. Successive Over-Relaxation Iteration.



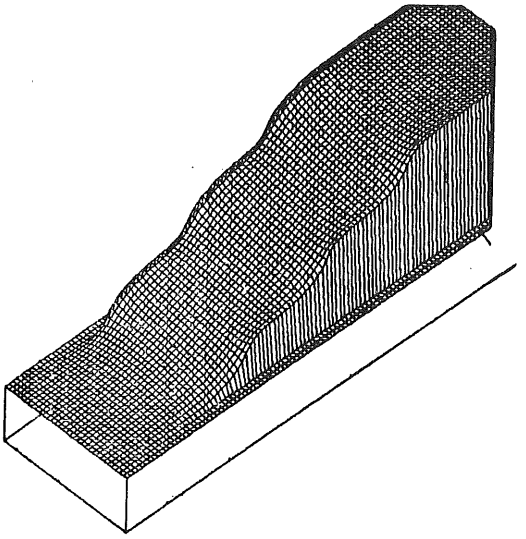


Figure 48 Three-Electrode-Pairs (β = 2). Current Stream Function.

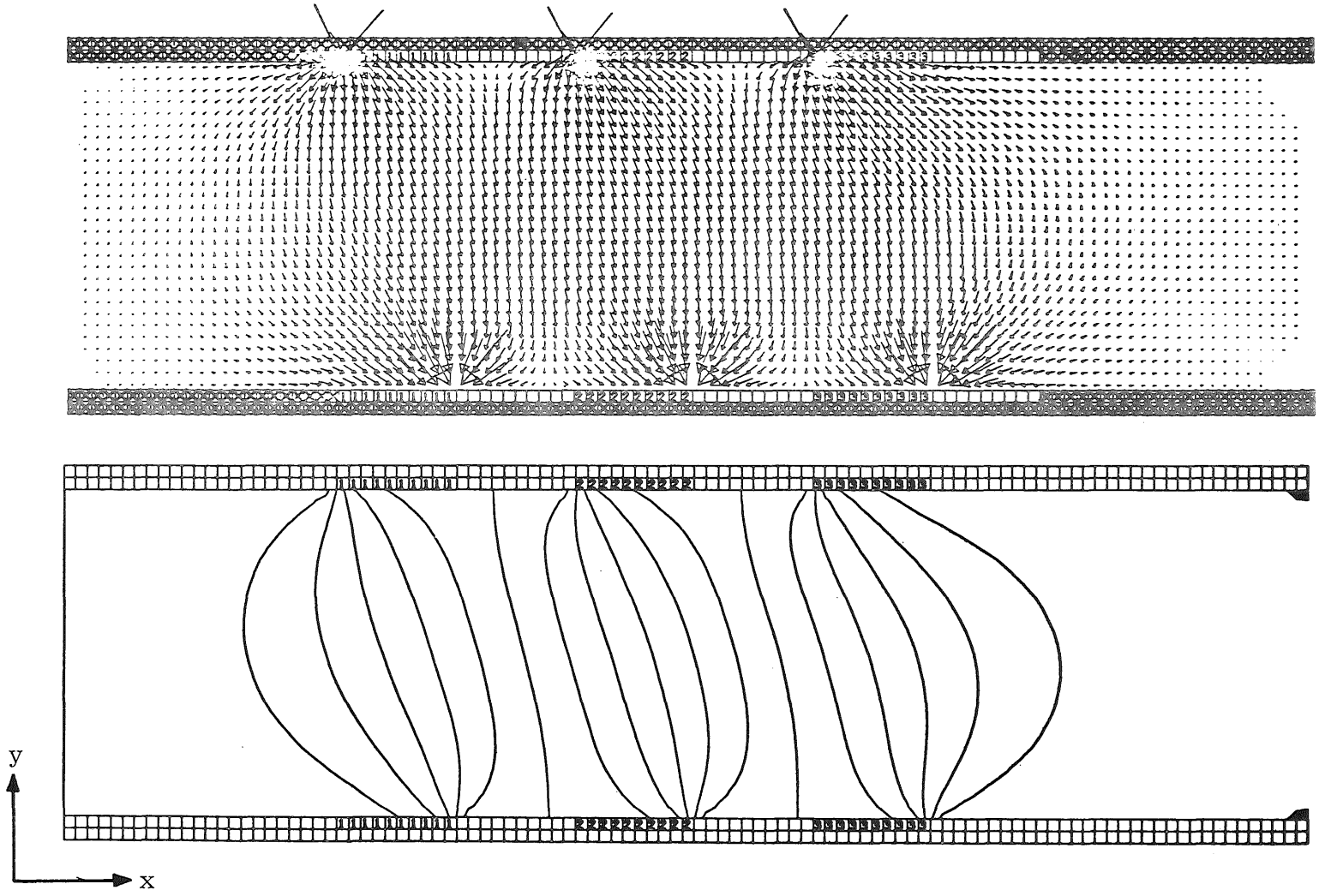


Fig. 49 Three Electrode-Pairs (β = 2).
Current Stream Function and Current Vectors

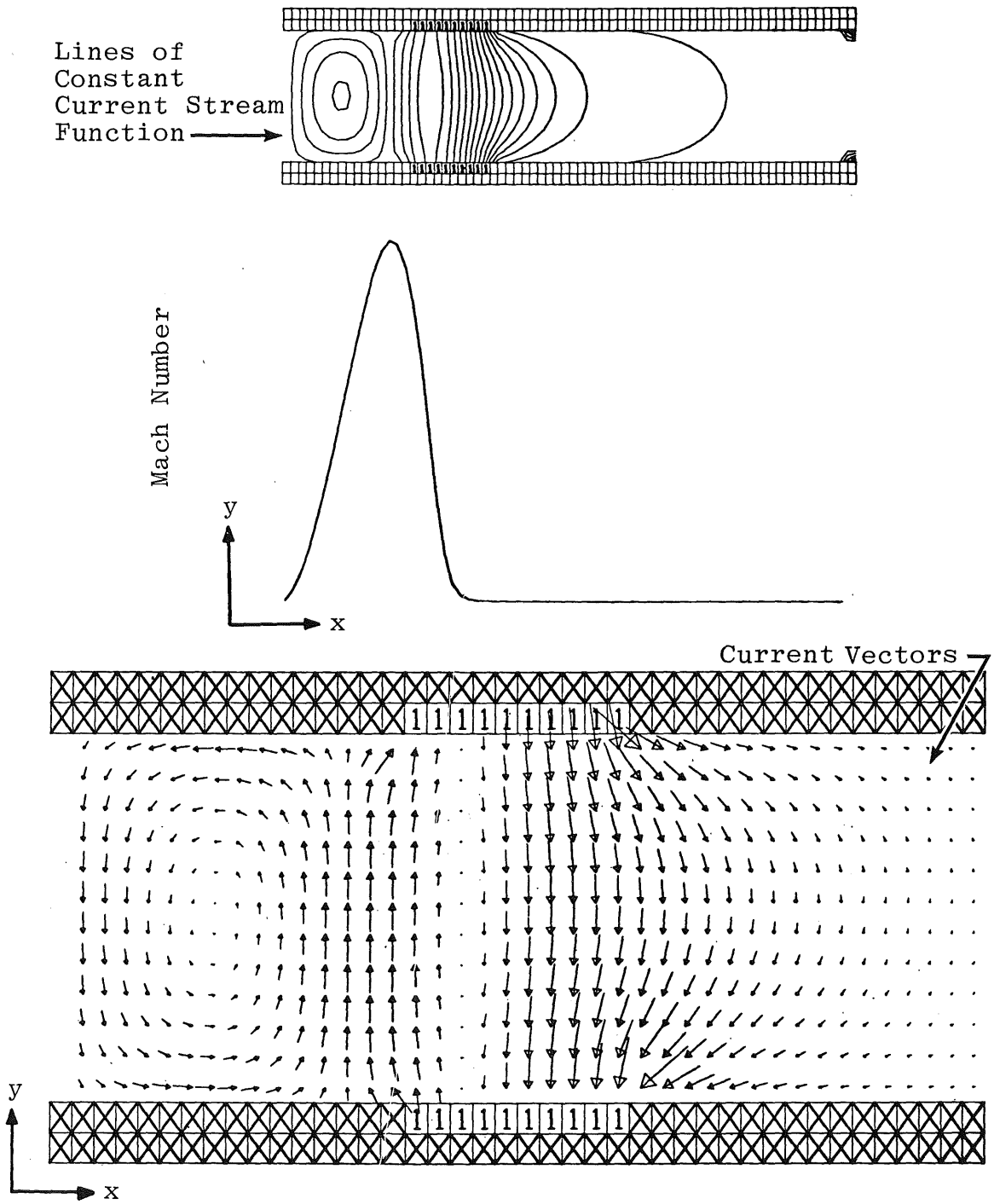


Fig. 50 Initial Formation of Current Eddies

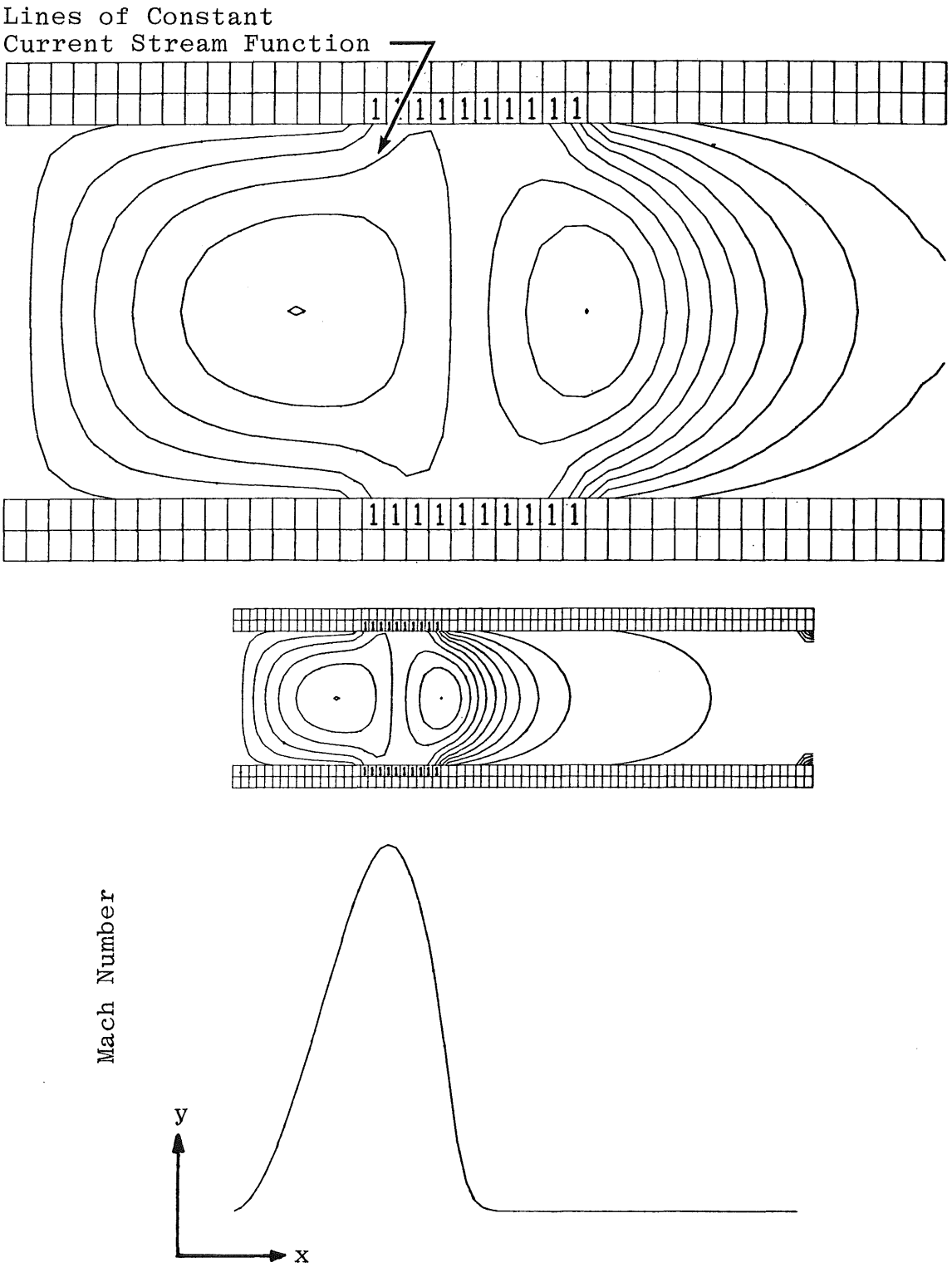


Fig. 51 Eddies in Motion with Shock Front

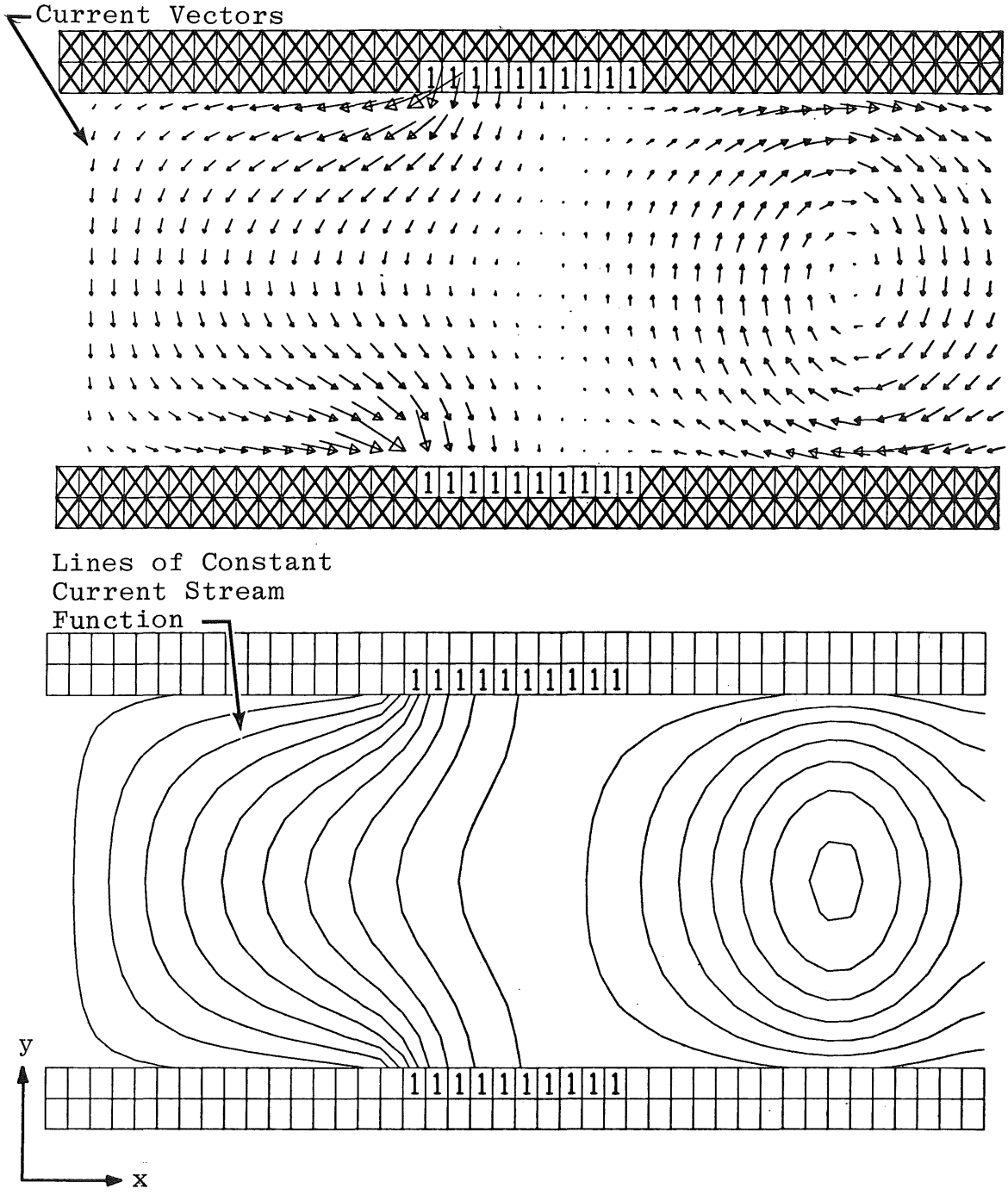


Fig. 52 Eddies Leaving the Channel

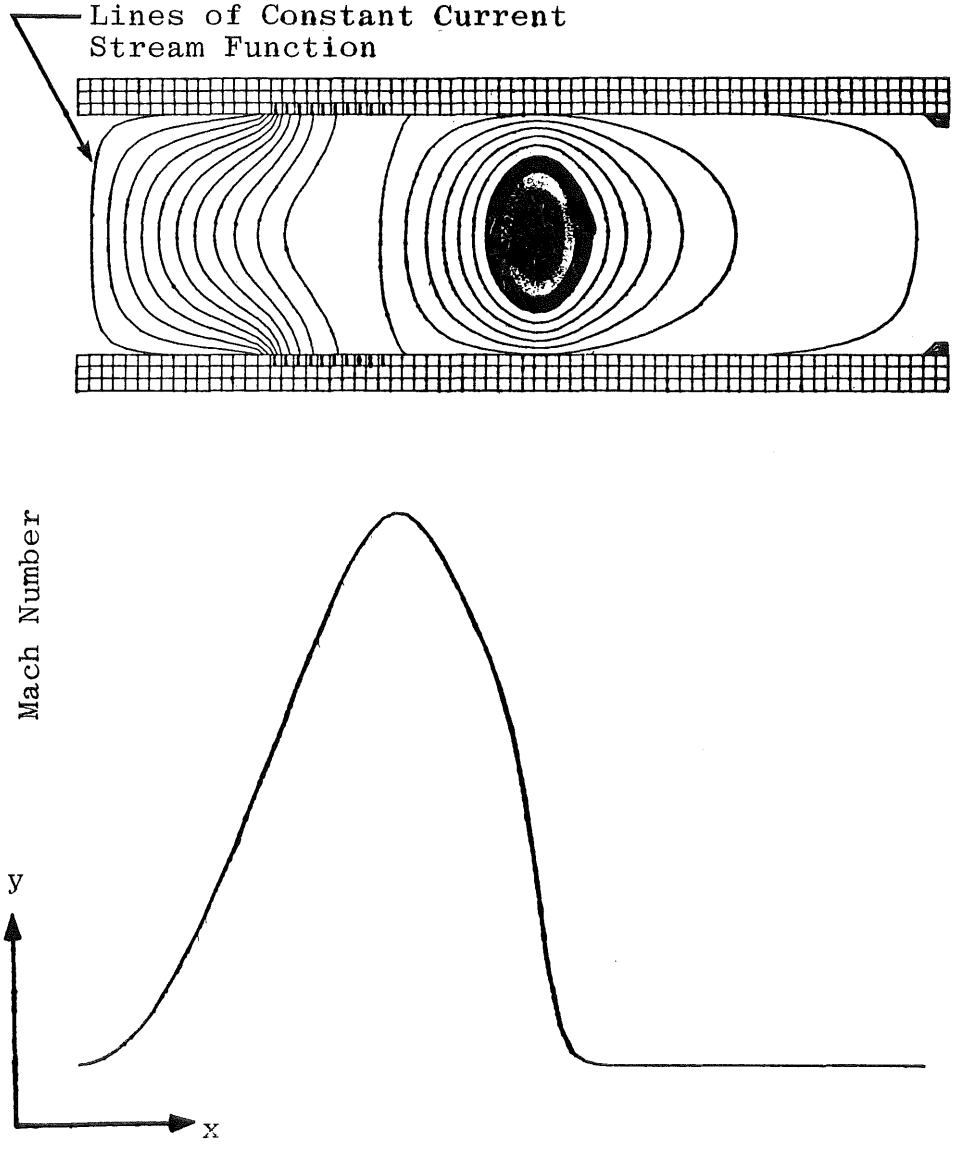


Fig. 53 Restoration of Initial Stream Current Function

different times as the shock wave passes through the channel. When the shock wave leaves the duct, the current stream function relaxes to its undisturbed initial state.

IV. MODELING OF AN MHD GENERATOR

The fundamental problems associated with modeling an MHD generator (Figure 54) concerns the treatment of:

(1) gas dynamic effects such as shocks and boundary layers,

(2) electromagnetic effects, and

(3) the transient coupling between these two sets of fields.

In Section (3), gasdynamic and electromagnetic phenomena were examined independently through application to problems categorized as either strictly aerodynamic or electromagnetic in nature. The strong interaction between gasdynamic, viscous and electromagnetic forces will now be examined.

Demonstration of the influence of the Lorentz force ($\bar{j}x\bar{B}$) on the flow field and, simultaneously, the influence of velocities and viscous shear on currents and electric fields is accomplished by investigating the following three cases (see Figure (55)):

(A) A nozzle-generator-diffuser system with five-electrode pairs is examined under inviscid conditions; enphasis is placed on modeling the entire energy conversion system. The applied magnetic field is shown in Figure (56) and design parameters are listed in Table (6).

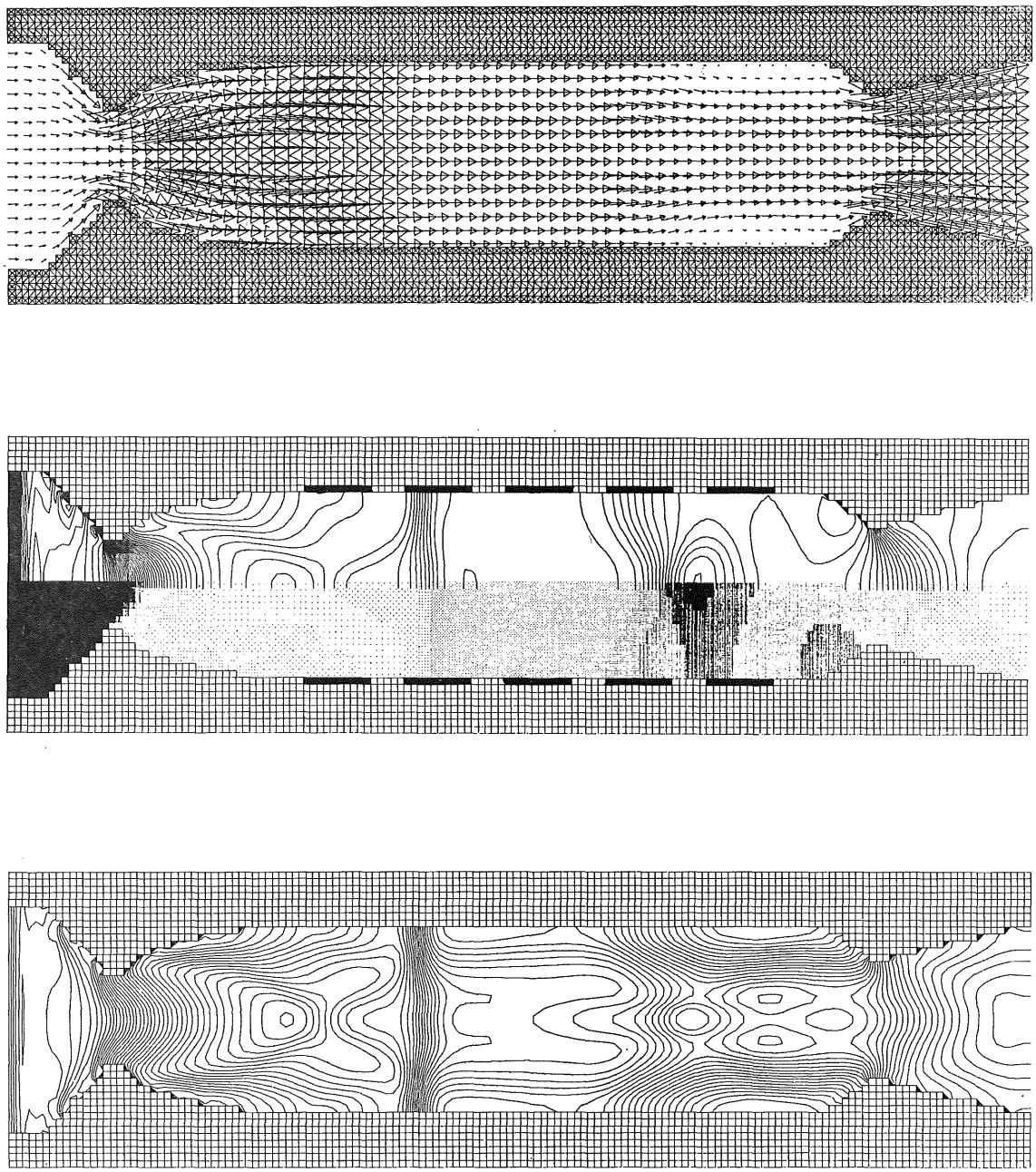


Figure 54 MHD Generator System

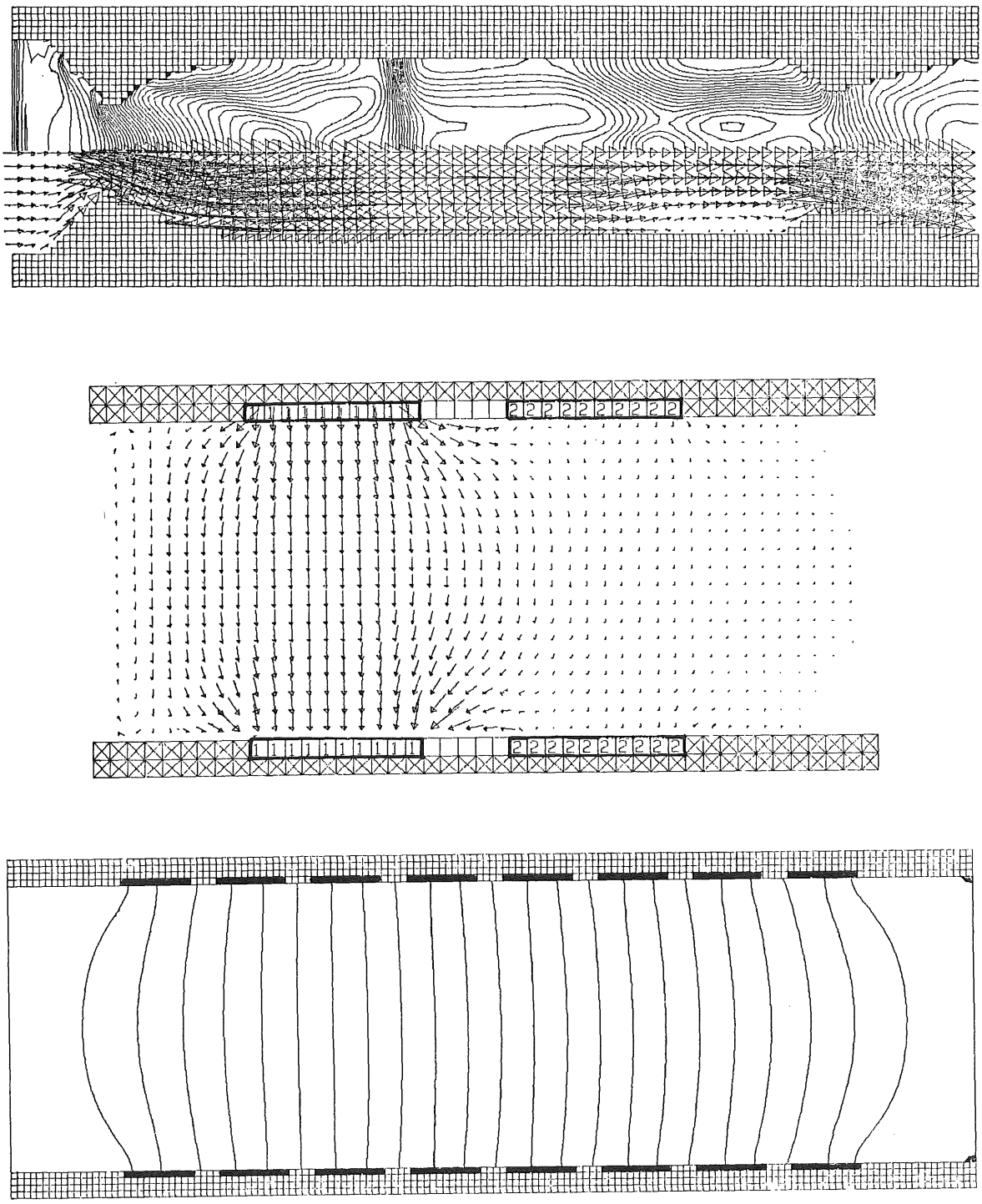


Figure 55 MHD Generator. Three Cases Modeled.

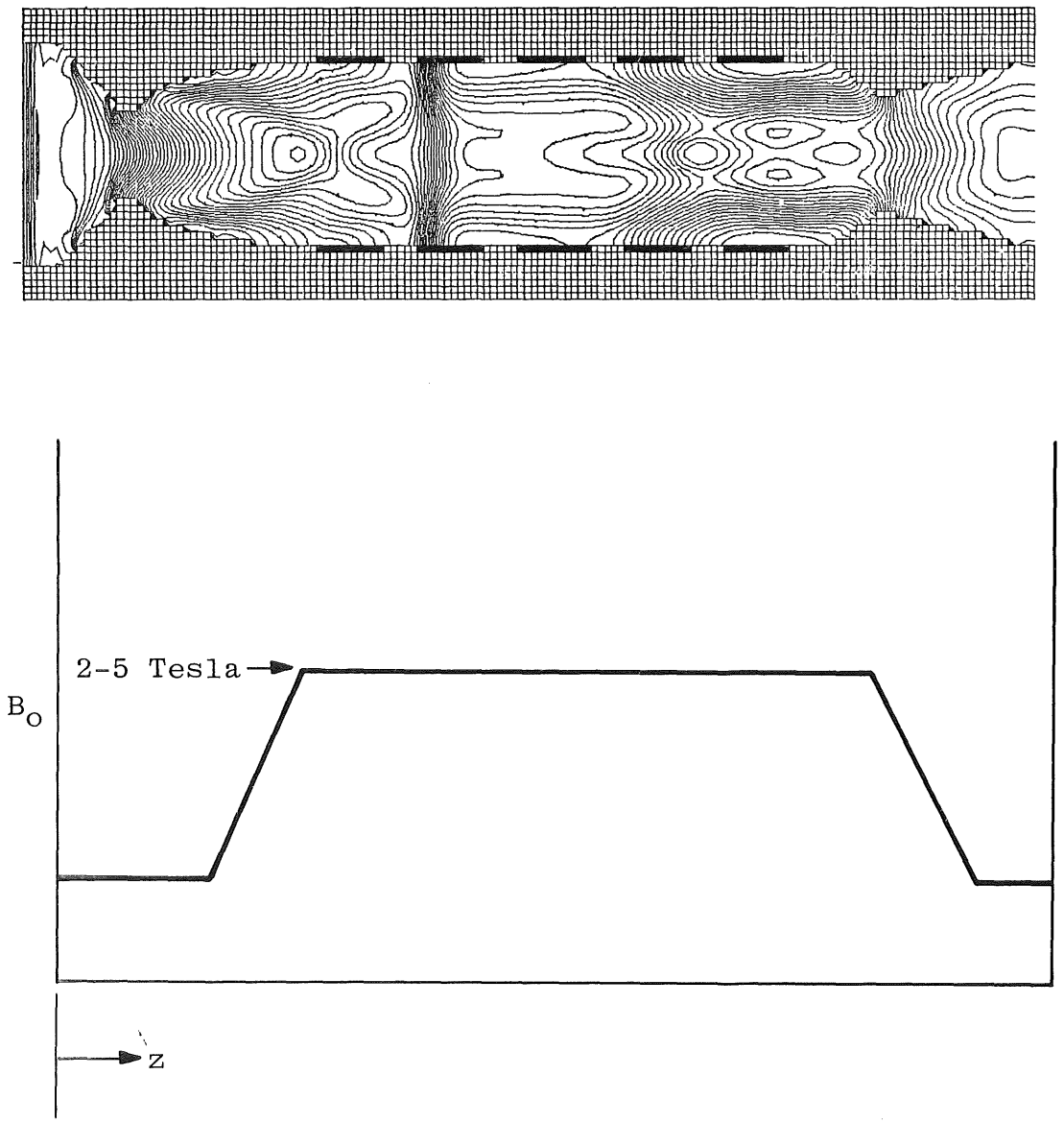


Figure 56 Applied Magnetic Field

TABLE 6. MAGNETOHYDRODYNAMIC GENERATOR CONDITIONS

Thermodynamic Conditions

Chamber		Ambient	
Pressure	5-10 atm	Pressure	1 atm
Temperature	2500°-3000°K	Temperature	270°K
Density	0.0005 gm/cm^3	Density	0.0013 gm/cm^3

Equation of State:	$P = \rho RT$
Specific Heat Ratio:	$\gamma = 1.15$
Gas Molecular Wt:	MW = 21

Geometry

Nozzle	Diffuser
Expansion Ratio: 2	Expansion Ratio: 2
Length: 10 cm	Length: 10 cm

Generator	Electrodes
Length: 200 cm	Length: 1.0 cm
Height: 20 cm	Height: 0.2 cm
Type: Faraday	Insulation Thickness: 0.4 cm

(B) An MHD channel containing two electrode-pairs. Start-up is achieved by applying an external magnetic field of strength: 2-5 Teslas and fluxing a gas of constant conductivity: 1-10 Mhos. The creation of current ($\simeq\sigma vB$) and subsequently the pondermotive (Lorentz) force $\bar{j}x\bar{B}$ is examined as a function of time.

(C) An MHD channel containing 8-electrode pairs. The steady state solution of currents, electric fields, ϕ and ψ under inviscid and viscous conditions is studied. The electrical conductivity and Hall parameter are considered functions of thermodynamic state properties and governed by the following relations:

$$\sigma = \frac{\sigma^*}{1+\beta^2}\left(\frac{\rho_{ref}}{\rho}\right)\left(\frac{T}{T_{ref}}\right) \tag{215}$$

$$\beta = \frac{B(tesla)}{2}\left(\frac{\rho_{ref}}{\rho}\right) \tag{216}$$

The viscous boundary layer was assumed turbulent and described by an eddy viscosity model employing the Prandtl mixing length:

$$\tau = \rho\varepsilon\frac{\delta u}{\delta y} \tag{217}$$

$$\varepsilon = \lambda_E^2\left|\frac{\delta u}{\delta y}\right| \tag{218}$$

V. RESULTS OF MHD MODEL

Results of the three cases modeled in Section (4) are now described.

5.1 Case (A): Nozzle-Generator-Diffuser System; Inviscid Conditions

Start-up of a generator, as for a wind-tunnel, consists of a shock moving down the channel and out the diffuser. Figure (57) illustrates a 3-D view of the shock (Mach number) and the current stream function. Figure (58) graphically describes: Mach contours, velocity vectors, ψ contours and current vectors. A three-dimensional view of ψ is shown in Figure (59). Figure (60) illustrates the coupling between gasdynamic and electromagnetic fields. The velocity vectors, current stream function contours and a 3-D view of the current stream function are shown at three time intervals for this three-electrode pair generator. Initially, a shock forms and moves to the exit of the nozzle just preceding the first electrode. An eddy current forms behind this shock (top of figure). As soon as the shock moves into the channel where the first electrode-pair is located, currents form on all three channels and are shorted between electrodes. As the gas flow continues, the currents flow between anode-cathode pairs and the short is eliminated.

5.2 Case (B): MHD Channel; Start-Up

Flow in a simple two-electrode-pair channel (20 cm x 40 cm) was examined when operating with an applied magnetic field turned off and

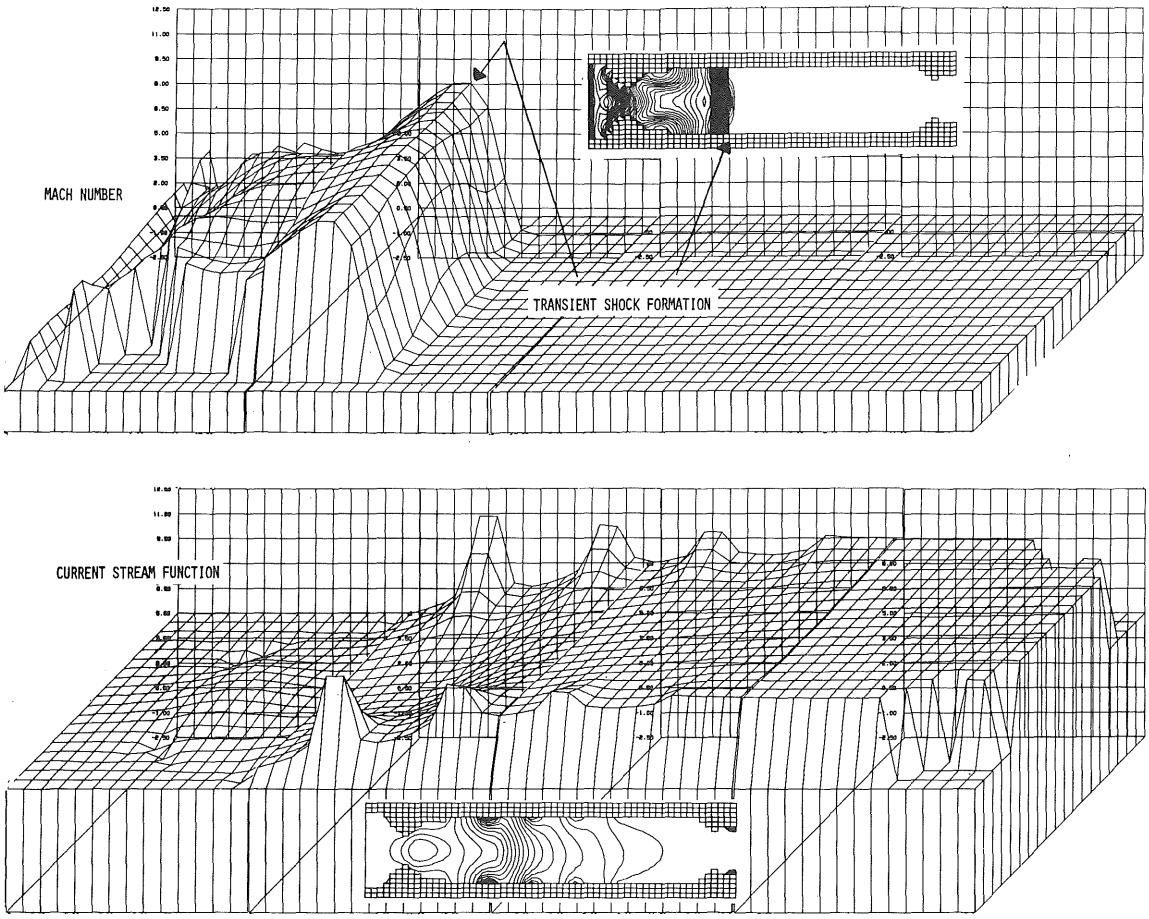


Figure 57 Transient Shock Moving Down a Five-Electrode Pair MHD Generator

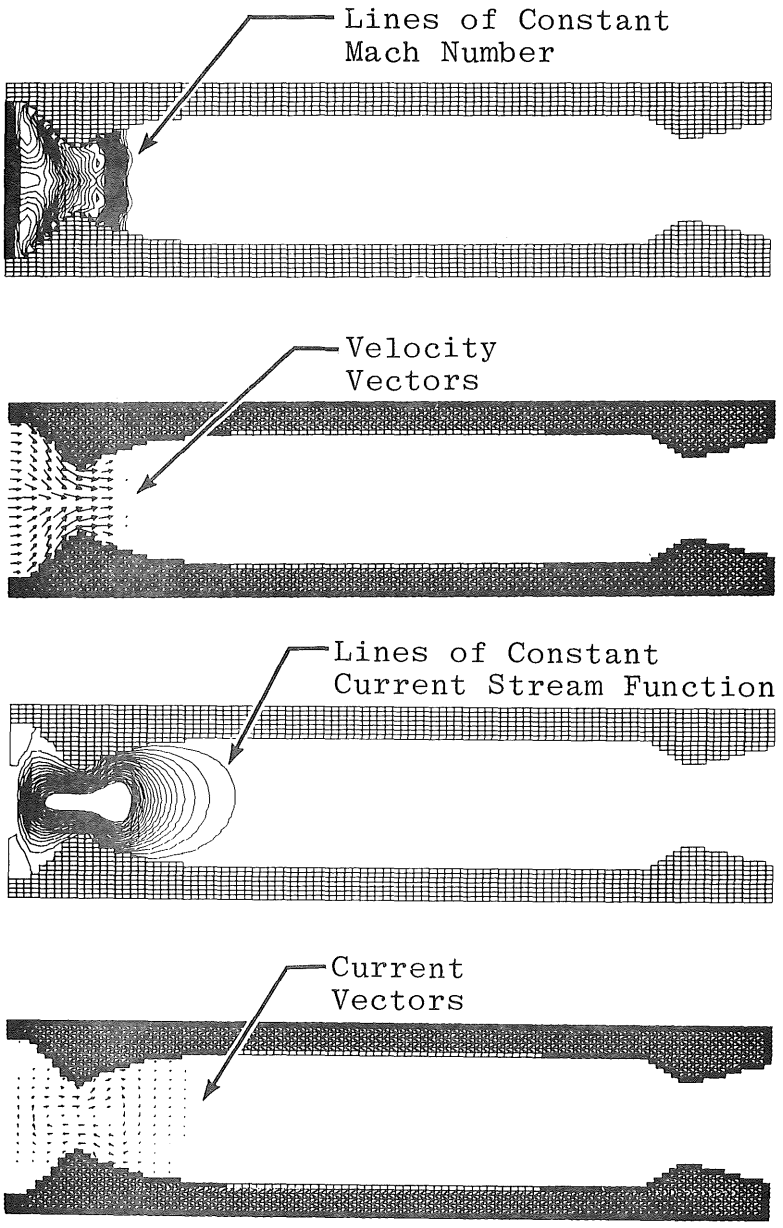


Figure 58 Transient Calculation of a Three-Electrode Pair MHD Generator

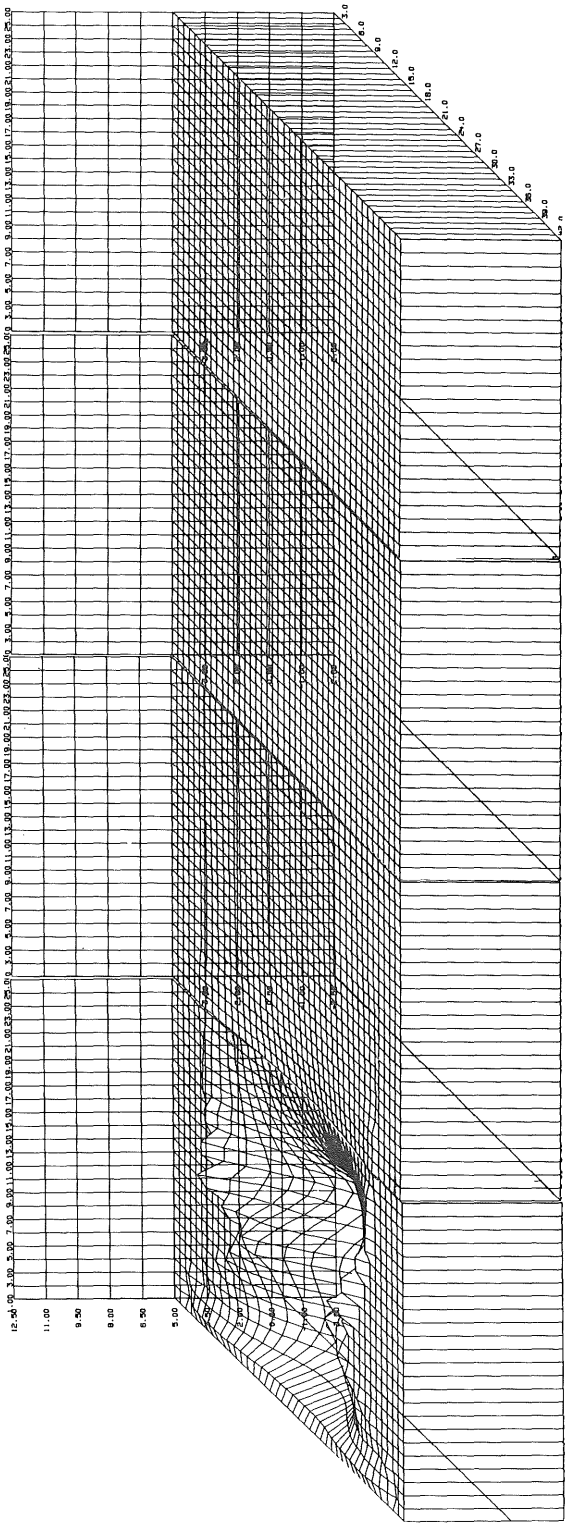


Figure 59 Three-Dimensional View of Current Stream Function for a Three-Electrode Pair MHD Generator

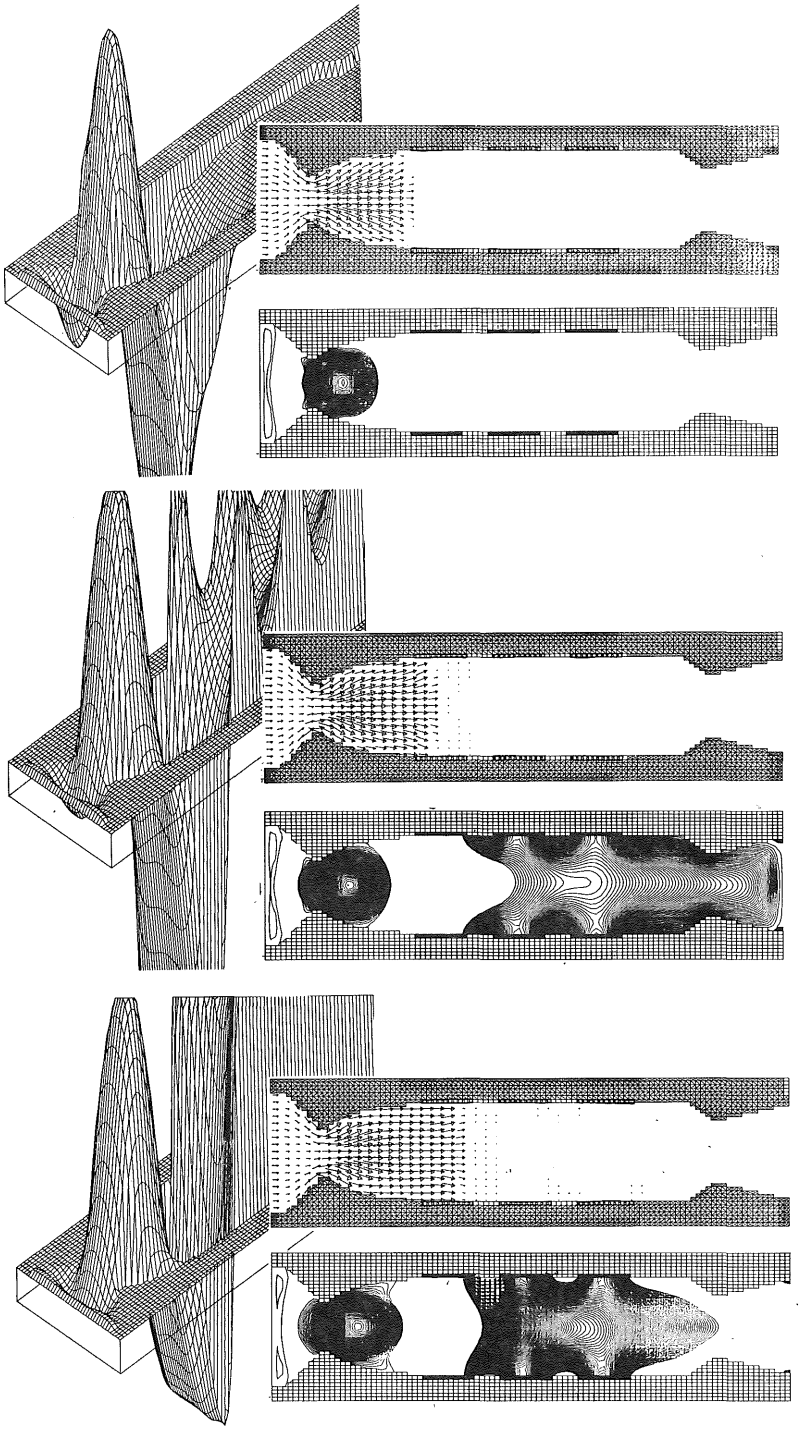


Figure 60 Transient Calculation of Coupled Gasdynamic and Electromagnetic Fields. Velocity Vectors and Current Stream Function (Contours and 3-D View).

then on. Figures (61), (62) and (63) illustrate the results. When the magnetic field is off, the flow reaches an unimpeded steady state velocity of 100,000 cm/sec as would be expected since no dissipative (inviscid, frictionless) forces exist. However, when an external magnetic field of 2 Tesla is applied, the velocity decreases down the channel since the pondermotive force decelerates the flow. The current stream function ψ on the boundary was determined by integrating the current flux across each electrode and recognizing that ψ is constant along an insulator. Initially, the velocity was zero so no net current flowed. As the velocity increased, the current increased. In turn, the current produced an impeding (Lorentz) force to the flow, and the velocity eventually reached equilibrium resulting in a steady state current distribution.

5.3 Case (C): MHD Channel; Turbulence

A channel containing eight electrodes was studied under inviscid and viscous (turbulent) conditions. Figures (64) and (65) contain results for both calculations. Considering the inviscid case, first, the current density ($\bar{j}$) current stream function (ψ) and electric potential (ϕ) distributions are illustrated in Figures (64) and (65). Employing a turbulent Prandtl mixing length model, the current distributions are perturbed as shown in Figure (65) for one-electrode pair.

Further investigations of the coupling nature between gasdynamic, viscous and electromagnetic forces is a logical extension of the brief results presented here.

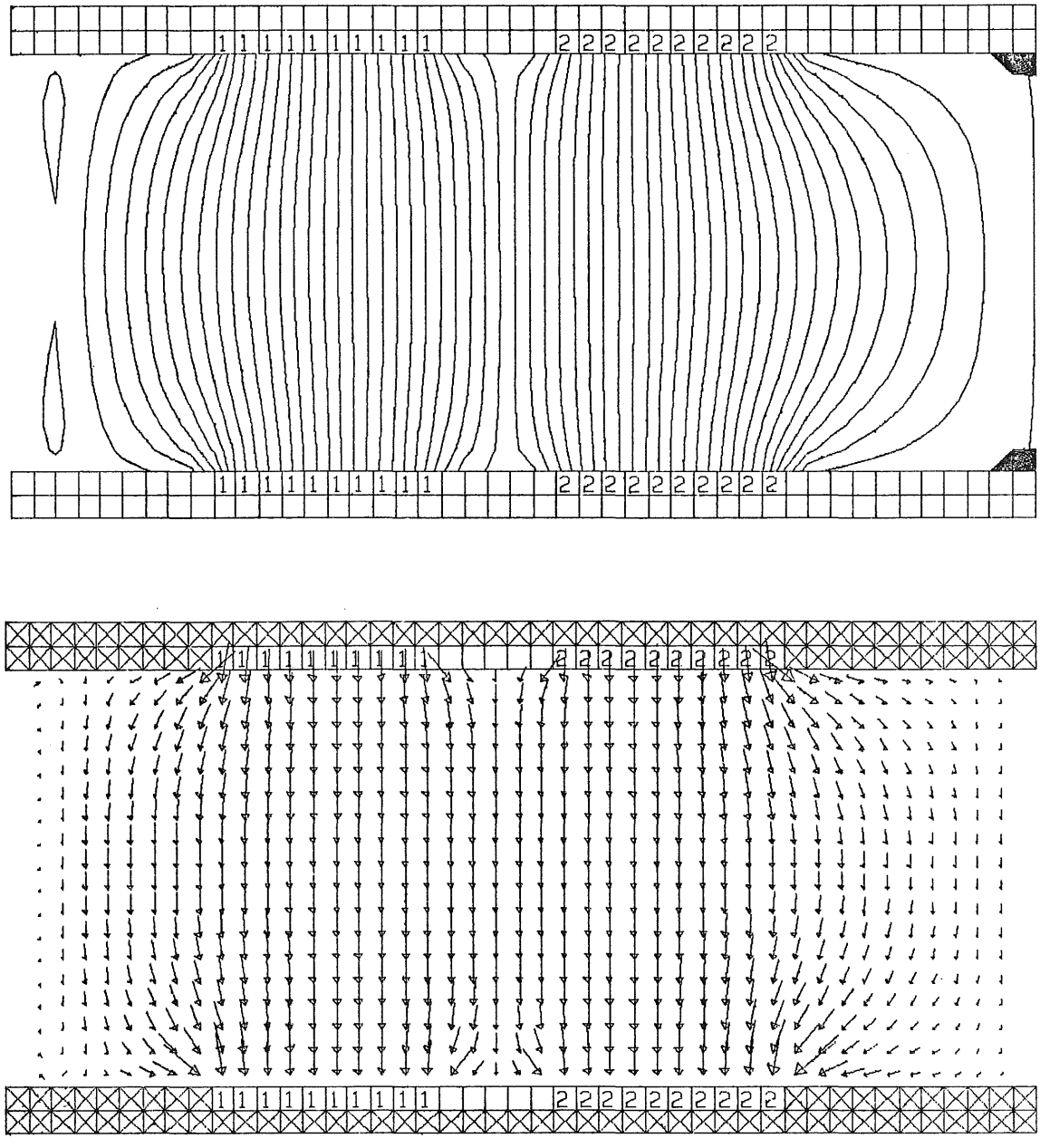


Figure 61 MHD Generator Start Up. Current Stream Function and Current Vectors

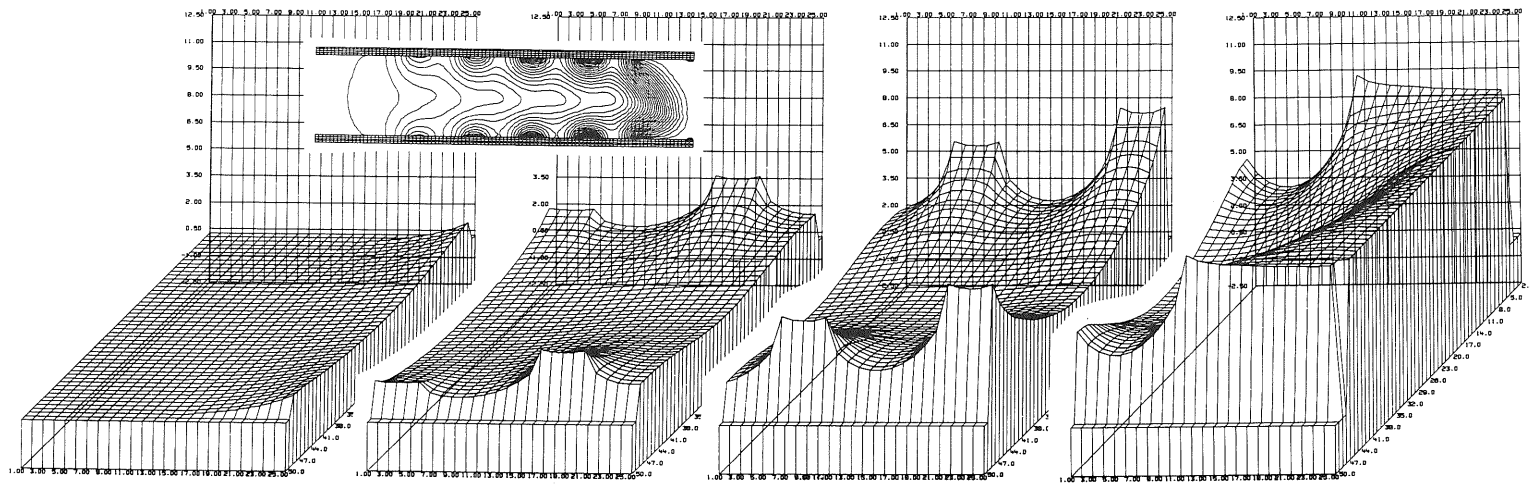


Figure 62 A Three-Dimensional View of the Current Stream Function for a Five-Electrode Pair Channel

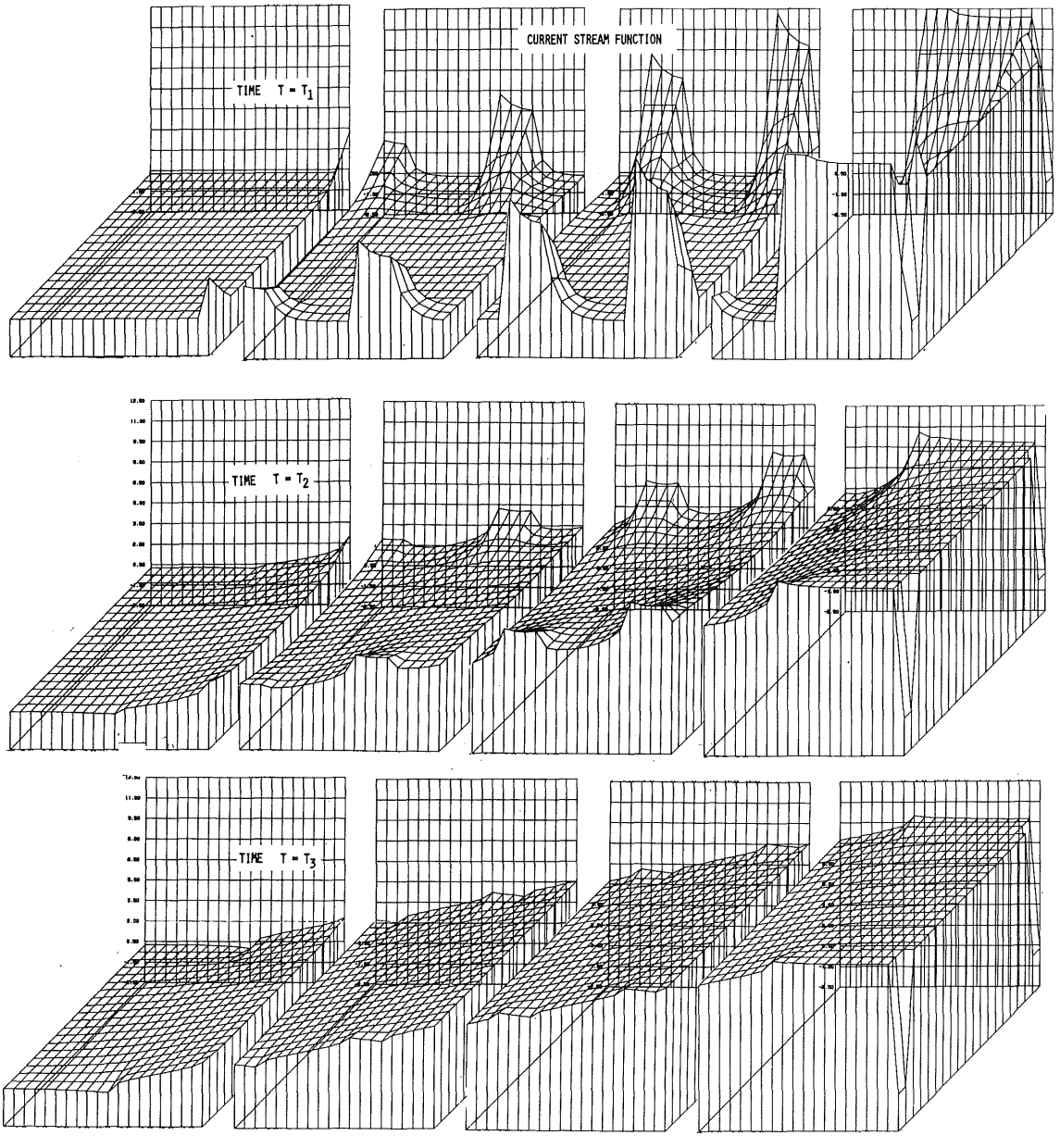


Figure 63 Transient 3-D Views of Current Stream Function for a Five-Electrode Pair Channel.

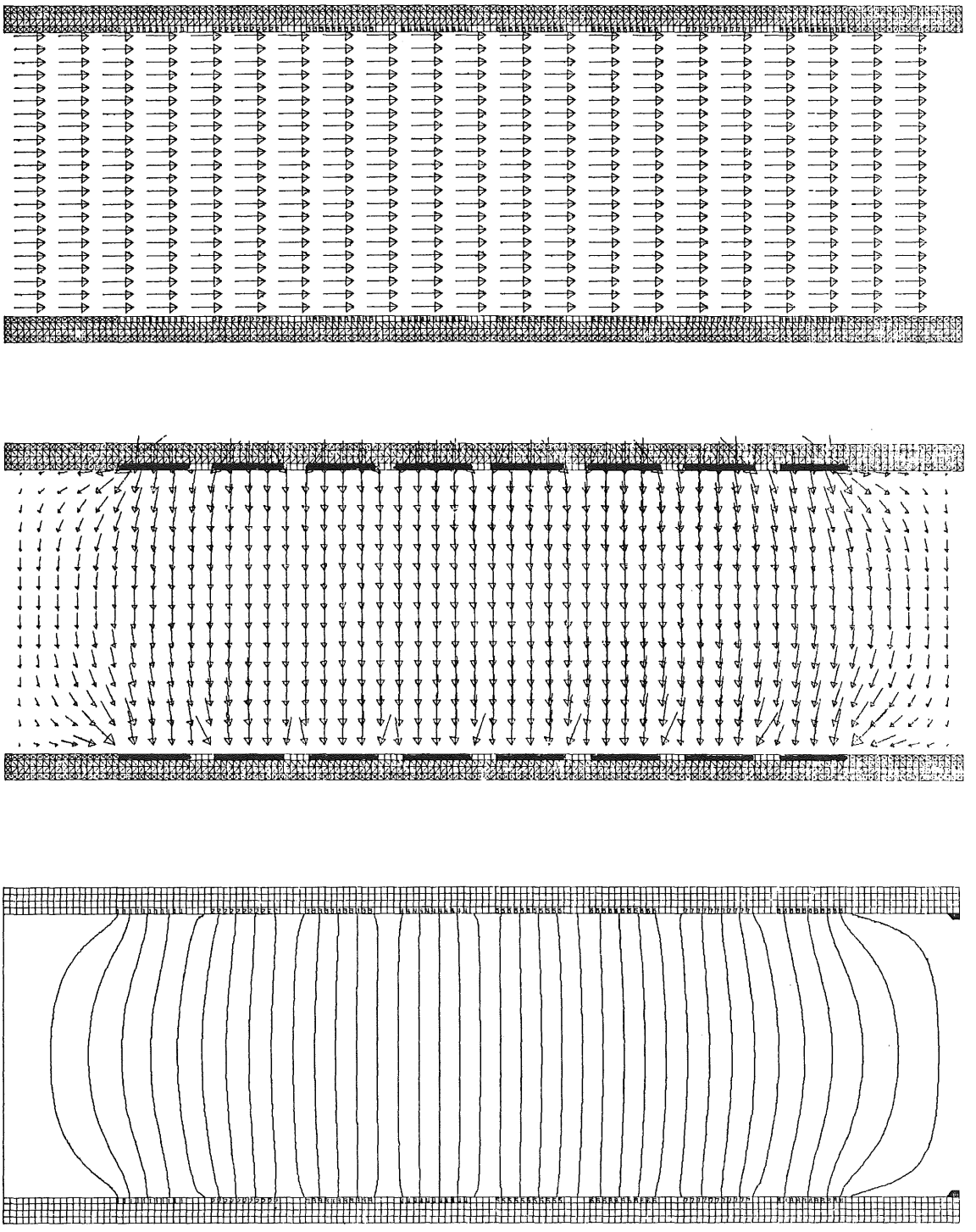


Figure 64 MHD Channel. Current and Inviscid Flow Field Distributions.

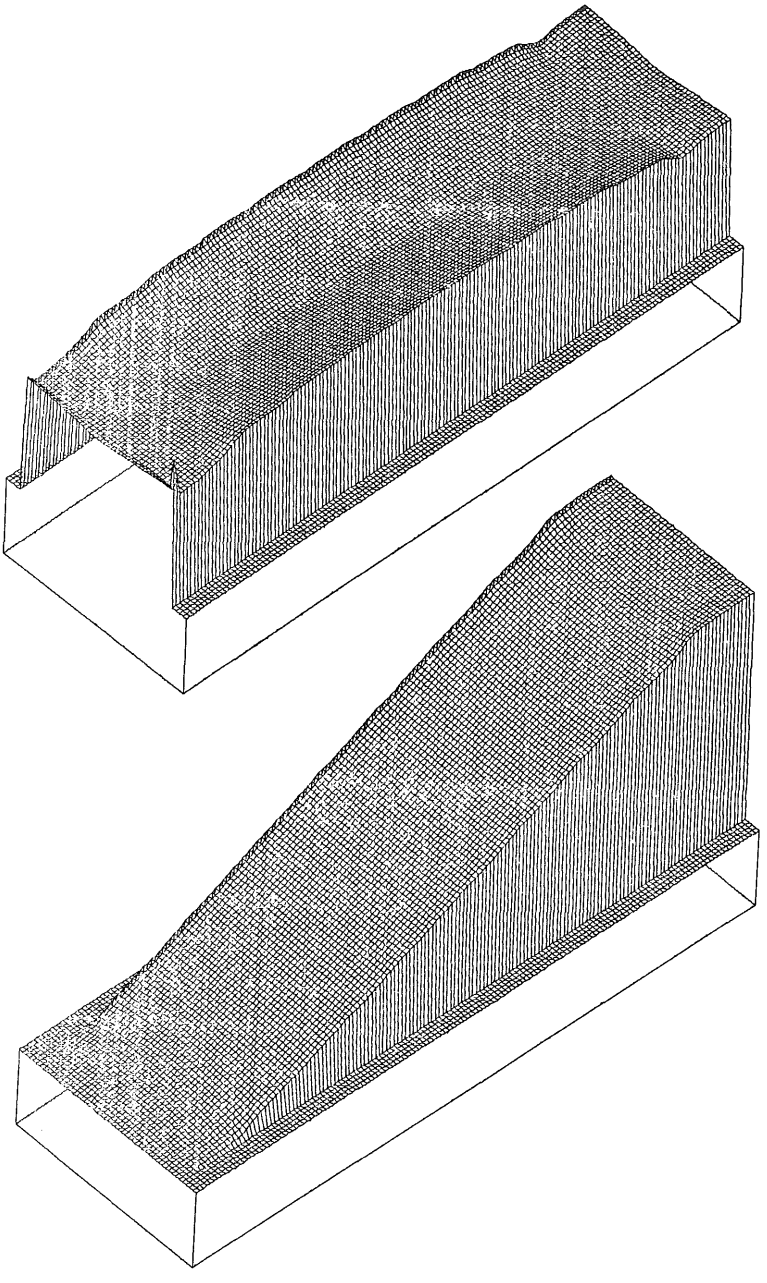


Figure 64 (Continued) Three-Dimensional Views of the Electric Potential and Current Stream Function

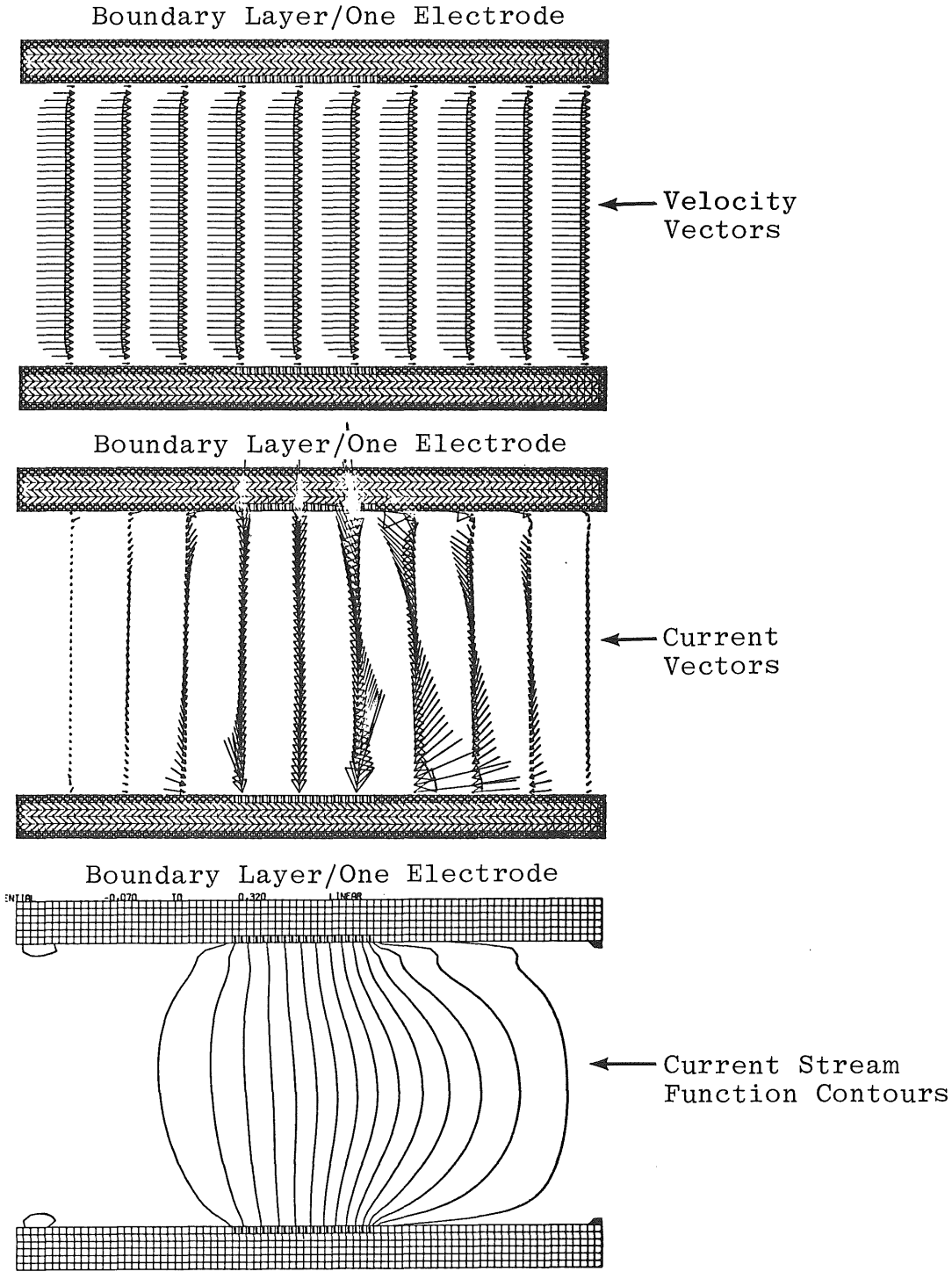


Figure 65 Influence of Boundary Layer on Current Distribution

VI. CONCLUDING REMARKS

6.1 Notes on the Code

Limitations to the numerical procedure discussed in this dissertation can be categorized into the following eight groups:

Computer Time

The primary disadvantage in employing a finite difference technique to the types of problems concerning engineers and physicists is computer time or computational speed. Where other methods arrive at solutions rapidly, this technique may require hours or even days. A two-dimensional transient problem has three coordinates: two spatial and one temporal. Given a mesh of approximately 100 cells in each direction and a calculation performed over approximately 1000 time iterations (cycles) results in 100 x 100 x 1000 = ten million cell-cycle solutions to the conservation of mass, momentum (r and z), energy, magnetic induction or elliptic equations. Since standard explicit finite difference routines compute on a CDC 6600 at a rate in excess of 1 millisecond per cell per cycle, a typical inviscid, non-MHD transient problem will require 10,000 seconds or two or three hours of central processor time.

However, it has been found that many problems do not require the resolution (10,000 cells) as depicted above nor must they necessarily be carried through to 1,000 time steps. Two-dimensional problems presented in this report range from as low as one minute to as much as three to four hours of CDC 6600 CPU time, depending on geometry,

boundary conditions, particle velocity and the inclusion or exclusion of viscosity, magnetic and/or electric fields. A three-dimensional transient problem would require from 30 minutes to 200 hours. With the inception of faster computers, the CDC computational times may be reduced by a factor of 5, 10 or even 50.

Since the advantages of finite difference techniques are quite evident in that they allow for a complete, reasonably unrestricted solution to the governing conservation equations, it would be only reasonable to expect some price to pay in return. If one, on the other hand takes into account the diversity of problems that can be solved by just this one procedure, as opposed to using numerous other methods or approaches, each restrictive in their very nature, the CP time requirements becomes a less significant handicap.

Inaccurate Material Properties:

Problems solved in this report all assumed a gas which could be characterized as obeying the perfect gas law, or represented by an equation of state which nearly describes this ideal fluid. Since, hydrodynamically, pressure is related to energy and density through this equation of state, a complete breakdown in accuracy occurs when the equation of state is unreliable. Similarly, a poor viscous model (real or eddy coefficient of viscosity) masks the influence of the viscous stress tensor resulting in a distorted boundary layer and adjacent inviscid flow field. The electric and magnetic fields are significantly influenced by the electrical conductivity. Severe error develops when the conductivity is unreliable. Other material properties perturb the flow field similarly.

Unrefined Grid:

Depending on the nature of the problem as dictated by the geometry and boundary conditions disturbing the flow, zone resolution may be so demanding; i.e., 10,000, 50,000, 100,000 cells, etc., that a course mesh (employing less cells) may not accurately reflect true hydrodynamic or viscous behavior because of discretization errors (first order truncation errors related to the cell size). In particular, a properly computed boundary layer may require from ten to twenty cells across its thickness in order for energy and momentum contributions to the entire flow field be accurately determined. However, in order to avoid large ratios in the cell size (a square cell yields a minimum truncation error, whereas a rectangle of aspect ratio > 2.5 may result in numerical distortion) the remaining inviscid flow field must be divided into cells of the same order as in the boundary layer; thus, a fully viscous 2-D calculation may require a grid resolution necessitating excessive computer time.

Boundary Conditions:

Unknown or poorly defined boundary conditions results in a costly trial and error procedure where the solution corresponding to a prescribed boundary condition may not be representative of the actual physical problem at hand. Further, a commonly employed uniform flow boundary condition may occur so far from the region of disturbance that the grid resolution becomes unwieldy.

Three-Dimensional Effects:

Unless a problem is planar or 2-D axisymmetric, variations in flow properties in the third dimension may render a 2-D solution meaningless.

Continuum:

The primary assumption of this finite difference technique is that the medium may be treated as a continuum and flow properties over a finite discrete cell do not vary significantly. However, when the mean free path of the fluid particle is not many orders of magnitude less than a cell dimension, as in a rarefied gas, the numerical integration of the conservation equations cannot be accomplished by the method discussed in this report.

Species Composition:*

Only one species was assumed for calculations performed in this study and thus only one equation of state was used. Considering numerous chemical species would require further significant code development and added complexity in tracking each species.

High Reynolds Number (Viscous Flow):

The boundary layer thickness δ is related to the characteristic body dimension by the Reynolds number. For a flat plate, Blasius computed δ to be approximately $5x/SQRT(Re_x)$ where x is the distance along the plate, δ/x is thus inversely proportional to the square root of the Reynolds number. For large Re ($> 10^4$) δ/x is small and creates the grid resolution problem of requiring $5/SQRT(Re_x)$ axial cells for every radial cell (if square cells are employed). If a grid having cells of

*Species in this case means one material and not one chemical element or molecule.

large aspect ratio is used, numerical distortion may be encountered. At critical Reynolds numbers, viscous instability occurs and a turbulent model must be used.

6.2 Summary and Conclusions

A numerical finite difference technique was developed to treat a wide variety of problems encompassing the disciplines of aerodynamics, gas dynamics, heat transfer, energy conversion and magnetohydrodynamics. Results of the numerous problems attempted and presented in Sections (3) and (5) reveal that this method has proven to be stable and accurate for a number of interesting applications. Major difficulties were encountered when problems such as the re-entry vehicle or MHD generator required more than 10,000 cells in order to preserve numerical accuracy. Computer time became significant in these cases and made numerical experimentation difficult, if not impossible. Boundary layers always presented a severe test to limiting the grid to less than 10,000 cells because the viscous region was usually at least an order of magnitude less than the inviscid region and the approach of varying the cell size through both regions created a significant risk of numerical distortion. Consideration was given to redefining the grid system based on dimensionless geometric, viscous and gas dynamic parameters, such as done by Spalding and Patankar (Ref. 14), but this approach was considered beyond the scope of this effort.

The versatility of this program was demonstrated by treating all Mach regimes: transient and steady state; viscous or inviscid; electromagnetic effects with or without Hall current and nonlinear

material property values. The computation did not decide, a priori, the particular regime or region in which it was calculating, but rather the phenomena were computed as they naturally developed as governed by physical laws which dictated their behavior.

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APPENDIX A

PAST WORK

The predecessor to the hydrocode developed in this dissertation was the HULL hydrodynamics computer code. The objectives and chronological history of HULL as reported in Reference 13 will be briefly outlined below.

The HULL code is a development of the Air Force Weapons Laboratory (AFWL), Kirtland AFB, New Mexico for the theoretical investigation of hydrodynamic phenomena of interest to the USAF. The principal architect of the sophisticated computer logic was Richard E. Durrett. The calculations represent numerical solutions to the inviscid, non-conducting equations of mass, momentum and energy conservation and are performed in an explicit time scheme in an Eulerian reference coordinate system. In order to maintain numerical stability, especially in regions of severe velocity gradients, calculations were performed in two phases, the first, computing a second order accurate Lagrangian integration and the second, fluxing mass, momentum and energy in order to retain the initial grid position; this fluxing procedure is tantamount to re-zoning.

Although the latest version of HULL is vastly superior to the abridged version developed for this research, only the 2-D numerical technique for a single material perfect gas was used. The complex HULL architecture and sophisticated operating philosophy was not employed. HULL is written in higher-level language and generates Control Data Corporation extended Fortran and assembly language routines. The HULL code in its 97th version treats multi-materials, three equations of state, equilibrium radiation diffusion and strength.

The evolution of HULL began in 1955 with the development of PIC (Particle In Cell) by Harlow. In the 1960's, W. E. Johnson authored an Eulerian version of SHELL which employed the two phase scheme of PIC. However, Phase I was numerically unstable until Matuska, in 1970, time and space centered calculations and thus evolved the HULL technique.

The conservation of mass, momentum and energy (Equations (A.1) through (A.4) supplemented with an equation of state are solved by a fully first-order accurate method developed by Matuska:

$$\frac{\delta}{\delta t}(\rho)+\nabla\cdot(\rho\vec{v}) = 0 \qquad \text{(A.1)}$$

$$\rho\frac{d}{dt}(\vec{v}) = -\nabla p+\rho\vec{g} \qquad \text{(A.2)}$$

$$\rho\frac{d}{dt}(e) = -\nabla\cdot(p\vec{v})+\rho\vec{v}\cdot\vec{g} \qquad \text{(A.3)}$$

$$i = (p,\rho) \qquad \text{(A.4)}$$

Equations (A.2) and (A.3) are solved in phase I for $\bar{v}$ and e (γ = constant). The integration is time and space centered which is vital to the stability of this computation. If the cell size is square and constant throughout the mesh, the solution of these equations will complete a first-order accurate Lagrangian calculation. Equation (A.1) is solved in phase II based on the updated values of e and $\bar{v}$ in phase I. The original coordinates are displaced by an amount equal to the velocity x time step. Next, by computing an appropriate amount of mass that is to be transported from cell to cell, the displaced coordinates are returned to their original positions. In addition to the mass

transported, an amount of momentum and energy is carried along analogous to the convection processes of mass, momentum and energy (see Figure (7)). This is the classical donor cell differencing technique. Redefining the coordinates to their original values, a somewhat less than rigid interpretation of the difference in Lagrangian and Eulerian derivatives would relate the convective terms in the Eulerian derivatives to the amount of fluxing. For example if the new coordinate points were not arbitrarily restored to their original values, then the amount of fluxing would differ from the convective terms appearing in Equation (A.1) through (A.3) Lindemuth (95) discussed the problems of a fixed or Eulerian space mesh where the convective terms are difficult to center in space and time in the explicit calculation and lead to instabilities or fictitious second order diffusion terms also pointed out by Richtmyer (3). The fluxing procedure described above avoids these two major shortcomings which are inherent in other Eulerian codes. Lindemuth further states the alternative of using a Lagrangian mesh but points out the awkwardness (instability) of the calculation as the mesh becomes greatly distorted. By proper rezoning of this mesh and conserving mass, momentum and energy, the calculation may remain stable. There are methods which retain their distinctive Lagrangian nature by not necessarily rezoning back to the original Eulerian coordinate system; they, however, may suffer either from non-conservation of mass, momentum and

energy or generation of significant non-physical internal energy (and subsequent diminishing kinetic energy) destroying the true physical conditions of the problem.

In performing the fluxing across cell boundaries, mass momentum and total energy are conserved. By examination of Equations (A.1) to (A.3), it is impossible to conserve the quantities of mass, momentum total energy and kinetic energy simultaneously. Kinetic energy is artificially dissipated representing a source of entropy production, especially in regions of large velocity gradients such as near shocks. This implicit viscous dissipation is inherent in all numerical schemes although other programs contain it in the form of an explicit artificial viscosity second order derivative.

As outlined in Section (1), the integration of time derivatives of the fluid properties density, velocity and energy, is performed in two phases. The Lagrangian derivative "d/dT" is computed in phase I; the convective or advective terms are computed in phase II; and the combination of both phases results in a first order accurate Eulerian integration. Space and time derivatives employ central differencing, whereas with time marching in the forward direction.*

Consider the fluid properties known at cycle (n), the method for updating these fluid property values at cycle (n+1) is summarized as follows: At some time t(n) and at cell (i,j), density, radial and axial velocity and energy are known throughout the entire grid. At a

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*Time variation of the electric and magnetic fields as well as thermal diffusion (all not included in HULL) is computed between phase I and II and employs the updated velocities and energy computed in the first phase.

later time t(n+1), where t(n+1) = t(n) + Δt (see Section (1.3)), the new values of the fluid properties are to be computed.

In order to time and space center calculations, values at the cell interfaces, such as pressure, density and velocity, are computed at t+Δt/2 (t(n+1/2)) and used in the Lagrangian integration. Employing i' and j' indices to indicate new coordinate positions resulting from the Lagrangian integration, the axial and radial velocity and the internal energy are computed at (n+1)based on values of $p,\rho,u,v,(\bar{j},B)$ and e predicted at cell interfaces.

The next step in the Lagrangian scheme would normally be that of transporting mesh vertices. However, to maintain an Eulerian integration and thus retain the original mesh configuration, the fluxing of hydrodynamic quantities is performed. This fluxing is tantamount to "rezoning" the displaced coordinates back to their original positions. After fluxing is performed and mass, momentum and energy (and magnetic induction) is convected, the displaced coordinates i', j' are returned to their original positions i,j. The amount of fluxing is determined by the velocities of the donor cells and the time interval over which the fluxing procedure occurs.

In conclusion, the HULL code was developed to treat high explosive detonation and nuclear blast phenomena. The equations and numerical formulation could have then just as easily been applied to the numerous aerodynamic and fluid mechanic problems confronting the aerospace engineer. Since 1965, however, other individuals have performed Eulerian and Lagrangian calculations in this field with varying degrees

of success, depending on the stability and convergence of the method used. It is precisely the unique nature of HULL (two phases: Lagrantian/rezone) which enables this method to treat the most severe flow fields in a stable and accurate manner. Finally the dozen or so individuals who spent many years and tens of thousands of CDC 6600 CPU hours developing the HULL hydrocode bears witness to the fact that development of a procedure for solving the conservation equations is, at best, an evolutionary process encompassing the efforts of many.

APPENDIX B

MATHEMATICAL DERIVATIONS

B.1 Time Rate of Change of Pressure

Employing a perfect gas equation of state, the internal energy, conservation of mass and rate of change of internal energy become:

$$i = \frac{1}{\gamma-1}\cdot\frac{p}{\rho} \tag{B.1}$$

$$\frac{\delta}{\delta t}(\rho) = -\rho\nabla\cdot\vec{v} \tag{B.2}$$

$$\rho\frac{\delta}{\delta t}(i) = -p(\nabla\cdot\vec{v}) + \frac{j\cdot j}{\sigma} - (\bar{\bar{\tau}}:\nabla\vec{v}) - (\nabla\cdot\bar{q}) \tag{B.3}$$

Differenting Equation (B.1)

$$(\gamma-1)\frac{\delta}{\delta t}(i) = \frac{1}{\rho}\frac{\delta}{\delta t}(p) - \frac{p}{\rho 2}\frac{\delta}{\delta t}(\rho) \tag{B.4}$$

Substituting Equation (B.4) and (B.2) into (B.3) and collecting terms

$$\frac{\delta}{\delta t}(p) = -\gamma p\nabla\cdot\vec{v} + (\gamma-1)\left[\frac{\vec{j}\cdot\vec{j}}{\sigma} - (\bar{\bar{\tau}}:\nabla\vec{v}) - (\nabla\cdot\bar{q})\right] \tag{B.5}$$

which represents the change in pressure as a function of time.

B.2 Electrical Boundary Conditions

The relationships between current and electric fields:

$$j_z = \frac{\sigma}{1+\beta^2}(E_z - \beta E_r) \tag{B.6}$$

$$j_r = \frac{\sigma}{1+\beta^2}(E_r + \beta E_z) \tag{B.7}$$

$$E_z = \frac{j_z + \beta j_r}{\sigma} \tag{B.8}$$

$$E_r = \frac{j_r - \beta j_z}{\sigma} \tag{B.9}$$

is derived by expanding

$$\vec{j} = \sigma(\bar{E} + \vec{v}\times\vec{B}) - \frac{\beta}{B}(\vec{j}\times\vec{B}) \tag{B.10}$$

The electrical field components are measured in a coordinate system moving with a velocity v.

Boundary conditions for a multi-electrode system in terms of either ϕ or ψ follows (Fig. 66). Ideal electrodes ($\bar{E}=0$) and insulators ($\bar{j}=0$) are assumed.

Stream Current Function Boundary Conditions

For a stream function ψ

$$j_z = \frac{\delta}{\delta r}(\Psi) \quad j_r = -\frac{\delta}{\delta z}(\Psi) \tag{B.11}$$

(A) conductors: $E_z=0$

$$j_z + \beta j_r = 0 \tag{B.12}$$

$$\frac{\delta}{\delta r}(\Psi) = \beta\frac{\delta}{\delta z}(\Psi) \tag{B.13}$$

(B) insulators: $j_r = 0$

$$\frac{\delta}{\delta z}(\Psi) = 0 \tag{B.14}$$

or ψ = constant.

Referring to Figure (66)

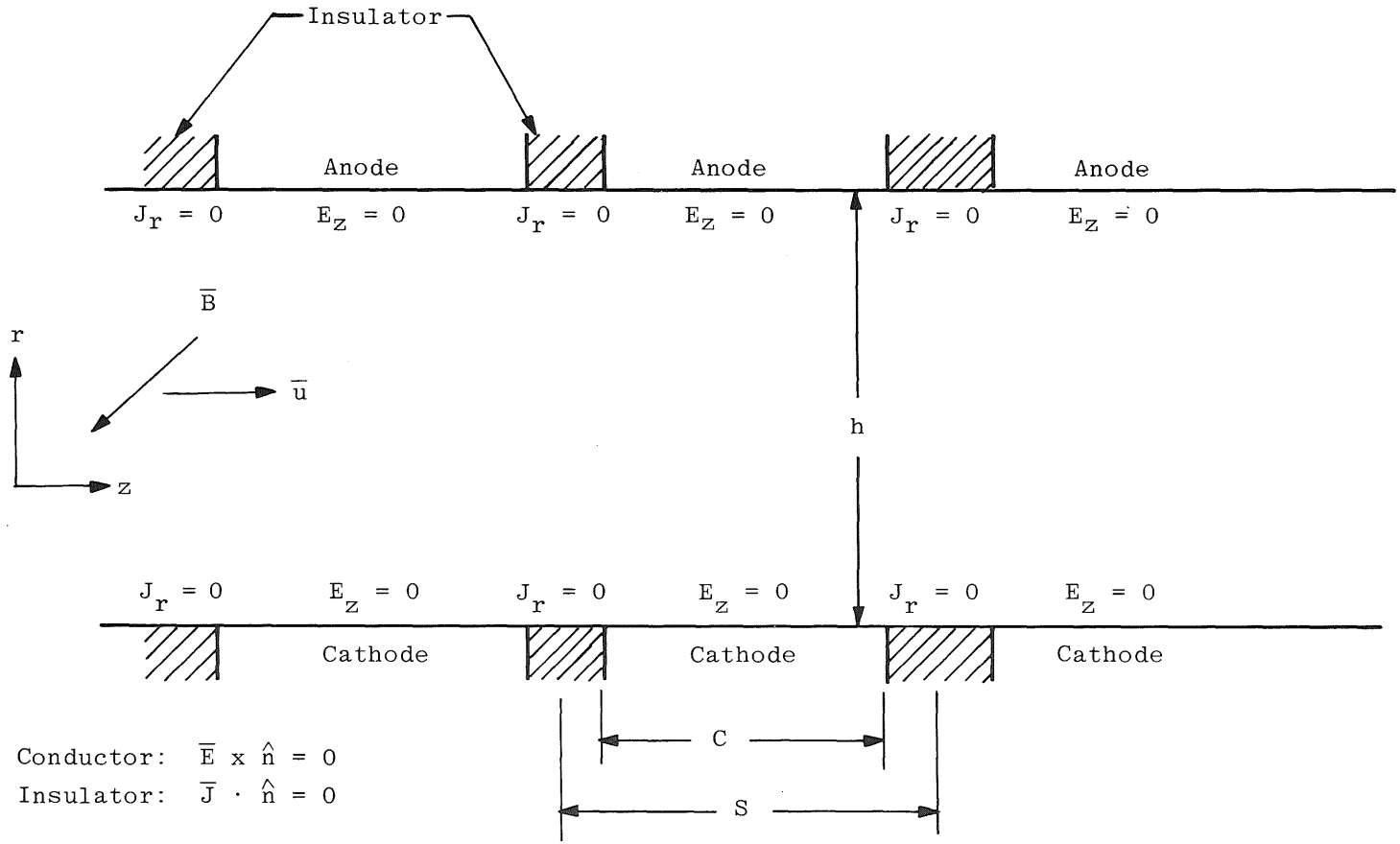
$$\Psi_2 = \Psi_1 + \frac{\delta}{\delta z}(\Psi)\Delta z = \Psi_1 - j_r\Delta z = \Psi_1 + I_r \tag{B.15}$$

where j_r is the net current in the radial direction flowing in the electrode-insulator pair. Similarly,

$$\Psi_4 = \Psi_3 + I_r \tag{B.16}$$

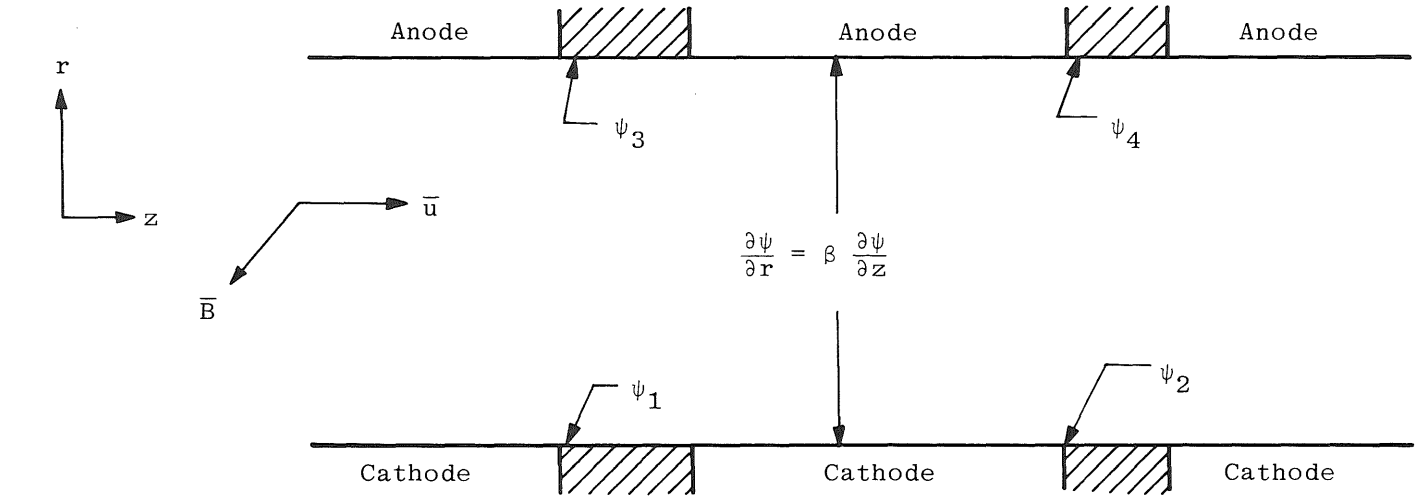
$$\Psi_3 = \Psi_1 + \frac{\delta}{\delta r}(\Psi)\Delta r = \Psi_1 + v_z \tag{B.17}$$

$$\Psi_4 = \Psi_2 + I_z = \Psi_1 + I_r + I_z \tag{B.18}$$

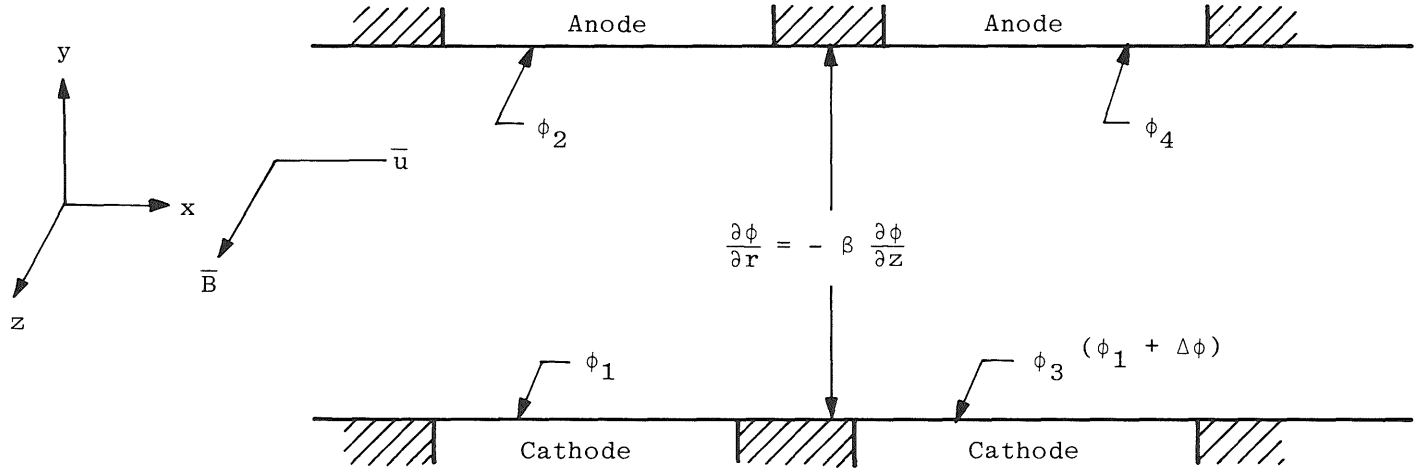


a. MHD Channel

Fig. 66 Electrical Boundary Conditions



b. ψ Boundary Conditions ($j_z = \frac{\partial \psi}{\partial r}$, $j_r = -\frac{\partial \psi}{\partial z}$)



c. ϕ Boundary Conditions ($E_z = -\frac{\partial \phi}{\partial z}$, $E_r = -\frac{\partial \phi}{\partial r}$)

Fig. 66 (Continued)

Electric Potential Boundary Conditions

$$E_z = -\frac{\delta}{\delta z}(\phi) \quad E_r = -\frac{\delta}{\delta r}(\phi) \tag{B.19}$$

(A) conductors: Ez = 0 or ϕ = constant

$$\phi_2 = \phi_1 + \frac{\delta}{\delta r}(\phi)\Delta r = \phi_1 - E_r \Delta r = \phi_1 + \Delta\phi_r \tag{B.20}$$

$$\phi_3 = \phi_1 + \frac{\delta}{\delta z}(\phi)\Delta z = \phi_1 + \Delta\phi_z = \phi_1 + V_z \tag{B.21}$$

(B) insulators: Jr = 0

$$\frac{\delta}{\delta r}(\phi) = -\beta\frac{\delta}{\delta z}(\phi) \tag{B.22}$$

Thus, for a Faraday generator

$$I_z = 0;\ \Psi_3 = \Psi_1;\ \Psi_4 = \Psi_2;\ \Psi_4 - \Psi_3 = \Psi_2 - \Psi_1 \tag{B.23}$$

equals the net current through the adjacent electrode.

For a Hall generator

$$\phi_3 - \phi_1 = \phi_4 - \phi_2 = V_z;\ \phi_2 - \phi_1 = -\phi_3 = \Delta V \tag{B.24}$$

where ΔV equals the voltage drop between the anode and cathode.

APPENDIX C

USER'S MANUAL

APPENDIX C

This appendix discusses the FORTRAN-IV computer program which generated the calculations presented in this report. Included are:

C.1 Program Flow Chart

C.2 Description of Program Routines

C.3 Description of FORTRAN Symbols

C.4 Discussion of Input, Output and Graphics

C.5 Test Cases

C.6 Program Suggestions and Diagnostics

C.7 Hull Difference Method Minority Report

C.8 FORTRAN IV Listing

Figure C.1 contains a flow chart of the program. Two overlays are employed, the first containing the numerics and the second, the plotting.

The core requirements are dictated by the size of arrays used in the labeled common block "CARRAY." For a 50 x 150 grid, the IBM-370 central memory requirement is 512K and the CDC 6600 is 260K. Reducing the grid to 30 x 75 reduces the core requirements to approximately 300K and 120K, respectively.

Each overlay is composed of approximately 3000 FORTRAN statements or a total of 3 boxes of cards for the complete source program.

TAPE AND DISK UNITS

UNIT	
5	Card input
6	Print output
14	Plot data written by subroutine GRAPH and read by subroutine GRID
15	Restart tape for dumping variables at cycle n (Subroutine OUTPUT) and reading in later (Subroutine INPUT) to restart at cycle n+1.

C.2 DESCRIPTION OF PROGRAM ROUTINES

This section discusses the routines contained in the computer code. The program consists of the following subroutine and functions:

MAIN - calls either hydro or plot routines

DRIVER - hydro exec routine

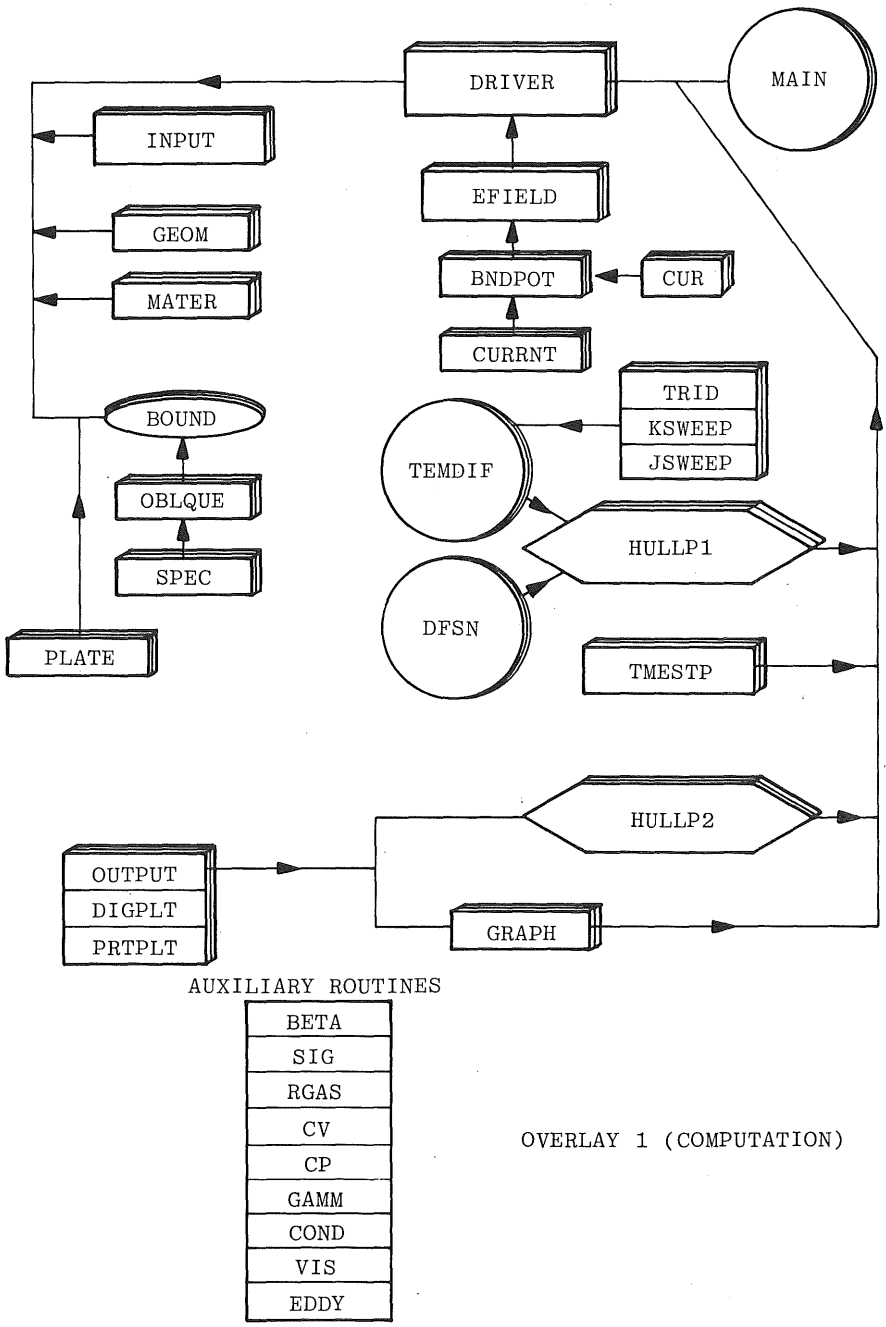


Figure C.1 Flow Chart

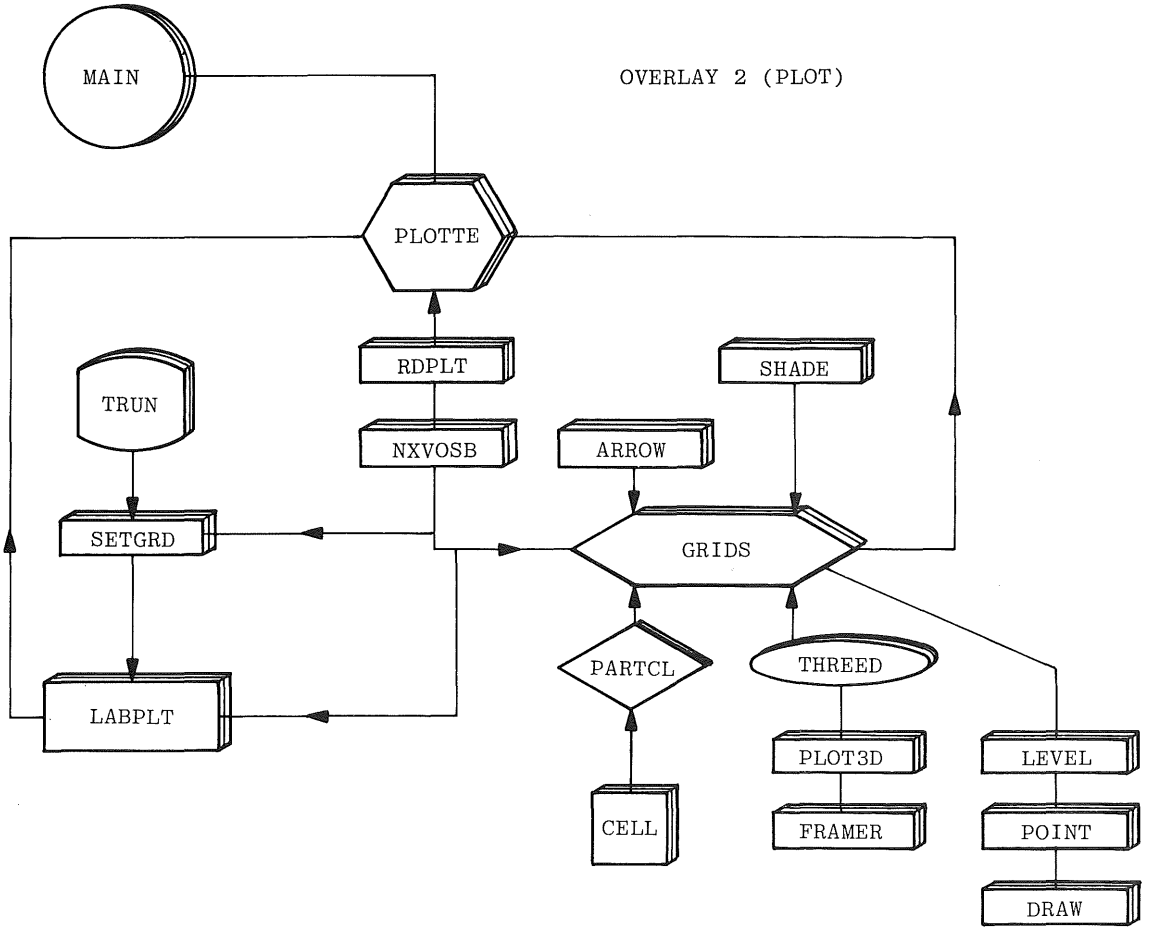


Figure C.1 Continued

INPUT - reads hydro input
GEOM - sets up grid
MATER - defines material properties (presently a dummy routine)
HULLP1 - performs hydro phase I
HULLP2 - performs hydro phase II
TMESTP - computes time step
BOUND - sets up boundary conditions
SPEC - assigns special values to variables and arrays
OBLQUE - determines oblique boundary conditions
EFIELD - performs SOR integration
BNDPOT - defines electrical boundary conditions
PLATE - defines electrode and insulator cells
CURRNT - computes currents and electric fields
CUR - computes radial current entering or leaving each electrode
DFSN - explicit solution of magnetic induction equation
TEMDIF - defines linear matrix for thermal diffusion
KSWEEP - implicit K sweep solution
JSWEEP - implicit J sweep solution
TRID - sets-up tri-diagonal matrix for SOR or ADI
VIS - laminar viscosity function
EDDY - turbulent eddy viscosity function
GAMM - specific heat ratio function
SIG - electrical conductivity function
BETA - Hall parameter
CV - specific heat at constant volume function
CP - specific heat at constant pressure function
RGAS - gas constant function
COND - thermal conductivity function
OUTPUT - writes output
GRAPH - stores plot data
DIGPLT - prints digital plot
PRTPLT - generates digital plot

WITH AUXILLARY PLOT ROUTINES:

PLOTTE - plot exec routine

RDPLT - reads plot input

SETGRD - sets up grid axis and labels

LABPLT - generates time history or spatial distributions

GRIDS - plots grids

TRUN - truncates axis coordinate values

SHADE - shades grids

NXVOSB - scales plot array

PARTCL - depicts tracer particles

CELL - locates cell (I,J) corresponding to a set of coordinates

ARROW - draws arrows

LEVEL, POINT, DRAW - contour plot package

THREED, PLOT3D, FRAMER - three dimensional plot package

PLOT AND AUXILIARY ROUTINES

Stromberg-Carlson 4020

FRAMEV - advances frame

LINEV - draws line

PLOTV - plots symbol

PRINTV - plots letter

RITSTV - controls letter spacing

CHSIZV - controls character size

DXDYV - scale routine

CALCOMP

CALCMP - executes numerous plot commands

PLOT - moves pen (in up or down position)

LINE - connects an array of points

SYMBOL - plots a string of symbols

See "SIMULATORS" Page 361

NUMBER - plots a number

GSIZE - calls for specific pen and paper

SECOND (CDC 6600) - gives cp time in seconds

TIMER (IBM 370) - gives cp time in seconds

1st OVERLAY

Referring to Figure C.1, main calls DRIVER which serves as the executive routine. Initially INPUT, GEOM, and BOUND are called to set up initial and boundary conditions and grid network. DRIVER then calls the hydrodynamic subroutines: HULLPI (phase I), HULLP2 (phase II), electromagnetic routines, EFIELD, thermal and magnetic diffusion routines: TEMDIF and DFSN, time-step calculation, TMESTP and the output routines: OUTPUT, DIGPLT, PRTPLT, and GRAPH (plot data).

Boundary conditions (BOUND) are defined as fixed, reflective or transmissive for each of the four boundaries. OBLQUE treats the curvature of oblique boundaries intersecting cells. Subroutine SPEC assigns special values to hydrodynamic or electromagnetic every cycle and BNDPOT assigns the electric potential or current stream function to electrodes and insulators. PLATE identifies the anode-cathode pairs.

Subroutine HULLP1 integrates the equations of motion in a Lagrangian reference frame. Subroutine HULLP2 transports mass employing the "donor-receivor" technique. The electromagnetic calculation is performed by EFIELD which solves the elliptic partial differential equation for the electric potential or current stream function. The method of Successive-Over-Relaxation was employed. If the time-dependent magnetic induction equation is solved, DFSN is called. Viscous effects are computed in HULLP1 employing the functions VIS or EDDY describing viscosity. Subroutine TEMDIF solves implicitly, the time-dependent heat conduction term (energy equation) by alternating directions in sweeping the grid: KSWEEP and JSWEEP. Subroutine TRID solves the tri-diagonal matrix formed.

Functions VIS, EDDY, GAMM, SIG, BETA, CV, CP, RGAS and COND compute properties at cell i,j based on the temperature, pressure, etc., at that cell.

2nd OVERLAY

Subroutine PLOTTE calls RDPLT for data input, sets up appropriate arrays for plotting time histories or spatial distributions or call GRIDS for contour, shading or 3-D plots. Subroutine SETGRD sets up the labeled axis. LABPLT draws the curves representing time history or spatial distributions of certain variables. GRIDS draws lines connecting nodal points and sets up data for vector, contour shade, 3-D and particle (tracer) plots.

NXVOSB is a scale routine which determines the location of points to be plotted. TRUN truncates a number to be used in labelling an axis. ARROW draws the head of vectors. PARTCL generates tracer particle and stores the particle trajectory data whereas CELL identifies the location of the tracer particle. Subroutines LEVEL, POINT and DRAW draw contour maps whereas subroutines THREED, PLOT3D and FRAMER construct 3-D plots. PLTMTX and PLT3D1 represent an alternate 3-D plot package. The contour plot package was developed by ARO, Inc., Arnold AFS, TN, whereas the 3-D plot packages were developed by the University of Texas and AEDC, Eglin AFB, FL.

C.3 DESCRIPTION OF FORTRAN SYMBOLS

This section contains a list of major FORTRAN symbols other than those to be discussed in the input section (C.4).

BO - theta magnetic induction

BPRES - magnetic pressure

BR - radial magnetic induction

BZ - axial magnetic induction

CMACH - Mach number

CMPR - cell compressive energy

COND - thermal conductivity

CV - specific heat at constant volume

DANGLE - angle of oblique boundary

DELTA - angle of oblique boundary

DR - radial dimension of cell

DEVU - axial velocity change due to deviatoric stress

DEVV - radial velocity change due to deviatoric stress

DT - time step

DZ - axial dimension of cell

E - energy/unit mass

ER - radial electric field

EZ - axial electric field

GR - radial gravitation (set = 0)

GZ - axial gravitation (set = 0)

INT - oblique boundary indicator

IOBK - oblique boundary indicator

JR - radial current
JZ - axial current
NCONV - convection time counter
NMAGN - magnetic time counter
NTHRM - heat conduction time counter
NVISC - viscous time counter
M - mass (new)
MIJ - mass (old)
P - pressure
PERM - permeability
PHI - electric potential
R - radial position of cell
RIMH - radial position at I - 1/2
RIPH - radial position at I + 1/2
RIP3H - radial position at I + 3/2
RDIST - radial position of oblique boundary
RGAS - gas constant
RHO - density
SIG - electrical conductivity
SPHU - axial velocity change due to pressure
SPHV - radial velocity change due to pressure
T - time
TEMP - temperature
THETA - angle of velocity vector
TOO - azimuthal stress
TRR - radial stress
TRZ - shear
TZZ - axial stress
U - axial velocity
V - radial velocity
VISC - viscosity
Z - axial position of cell

C.4 DISCUSSION OF INPUT, OUTPUT, AND GRAPHICS

Card input with FORTRAN symbols and format is defined below. Examples follow later in this report.

INPUT (HYDRO)

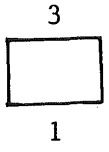
UNITS G(GM), C(CM), S(SEC), E(ERG), GA(GAUSS), P(POISE), O(OHM), M(METER), K(DEG K), A(ATM), D(DYNES), V(VOLTS), AC(ABCOULOMB)

CARD ONE (15A4)

TITLE	1-60	TITLE IDENTIFICATION	-

CARD TWO (1615)

KMAX	1- 5	number of cells in radial direction	-
JMAX	6-10	number of cells in axial direction	-
IAXI	11-15	(0) cartesian, (1) cylindrical coordinates	-
IPTSF	16-20	(1) current stream function, (2) electric potential	-
ISYM(1)	21-25	boundary conditions (0) fixed	-
ISYM(2)	26-30	(1) transmissive, (-1) reflective	-
ISYM(3)	31-35	for bottom, left, top, right boundaries	-
ISYM(4)	36-40		-
NVECT	41-45	(0) no oblique boundary, (1) top oblique, (2) top and bottom oblique	-
NPDIM	46-50	(0) no plot tape, (1) plot tape	-
MCALC*	51-55	type calculation: (viscous, EMF)	-
IRST**	56-60	(-1) write restart tape, (+1) read restart tape	-
IOBQ	61-65	(0) no obliq bdry, (+1) oblq bdry, (-1) no slip	-
IPOT	66-70	(0) no emf, (N) every Nth cycle, the potential or stream function is solved for.	



*The program was designed to eliminate the viscous or electromagnetic logic by selecting MCALC accordingly:

0 INVISCID
1 LAMINAR
2 TURBULENT

3 INVISCID
4 LAMINAR
5 TURBULENT

MAGNETIC INDUCTION

6 INVISCID 7 LAMINAR 8 TURBULENT	ELECTRIC POTENTIAL OR CURRENT STREAM FUNCTION

A viscous or magneto-stress calculation takes roughly twice as much CP time per cycle as a simple inviscid problem. Solving the electric potential or stream current function may take even considerably more time.

The "restart" capability is a means in which long executing jobs may be run in segments. As an example, given a 4-hour job which is to be run in 8 - 1/2 hour segments. Initially, IRST is set = "-1" and the program is run NMAX cycles. At the end of the run (NPRN $\leq$ NMAX) a tape on unit 15 writes all appropriate information in order that the calculations may continue later. In the next segment, IRST is set = "1" and the same card input along with the restart tape (unit 15) initiates the next sequence of calculations. After this calculation is completed, a new "dump" on tape 15 is performed and further calculations proceed in the same manner. No changes are required to the deck after IRST is set = 1 and the deck can be read in repeatedly in 1/2 hr, 1 hr, etc., segments.

IF IOBQ $\neq$ 0 READ CARD THREE A:

CARD THREE A

RD	1-10	r coordinate of oblique boundary*	C
XD	11-20	z coordinate of oblique boundary	C

IF IPOT $\neq$ 0 READ CARD THREE B:

SPACE	1-10	number of cells per electrode	-
SPINSL	11-20	number of cells per insulator	-
BASEP	21-30	number of EMF integrations on the first cycle	-
DPOT	31-40	number of EMF integrations on the ensuing cycles	-
DVOLT	41-50	dummy	-
JPLMIN	51-55	initial conductor (or insulator) cell	-
JPLMAX	56-60	final conductor (or insulator) cell	-

CARD FOUR (815)

NPRN	1- 5	print interval in cycles	-
KPDEL	6-10	print for every kth cell	-
JPDEL	11-15	print for every jth cell	-
NPLOT	16-20	plot tape interval in cycles	-
NDIGPL	21-25	(0) no digital plot, (1) digital plot	-
NMAX	26-30	terminal cycle	-
NCYCLE	31-35	initial cycle	-

*If electrodes are employed (IPOT$\neq$0), at least two boundary cells must be defined.... see Fig. C.9, page 227.

CARD FIVE (8E10.4)

DZØ	1-10	cell spacing in axial direction	C
DRØ	11-20	cell spacing in radial direction	C
ZMIN	21-30	minimum axial location	C
RMIN	31-40	minimum radial location	C
MINDT	41-50	minimum time step	S
MAXDT	51-60	maximum time step	S
STAB	61-70	stability factor	-
TZERO	71-80	initial time	S

CARD SIX (8E10.4)

RHOØ	1-10	density	G/C3
VZ	11-20	axial velocity	C/S
VR	21-30	radial velocity	C/S
EØ	31-40	energy/mass	E/G
BØ	41-50	magnetic induction - theta	G
BRØ	51-60	magnetic induction - R	G
BZØ	61-70	magnetic induction - Z	G

CARD SEVEN (4E10.4)

VISCØ	1-10	viscosity	P
PERMØ	11-20	permeability	-
MW	21-30	molecular weight	-
ARFV	31-40	artificial viscosity (0) off, (1) on	-

CARD EIGHT TO TEN (415,/,7E10.4,/,5E10.4)

K1	1- 5	special assignment of cell variable values	-
J1	6-10	from K1 to K2 in radial direction and J1	-
K2	11-15	to J2 in axial direction	-

J2	16-20		-
BRHOØ	1-10	same variables as defined before, e.g. BEØ and	G/C3
BVZ	11-20	EØ	G/C
BVR	21-30		G/C
BEØ	31-40		E/G
BBØ	41-50		G
BBRØ	51-60		G
BBZØ	61-70		G
BVISCØ	1-10		P
BPERMØ	11-20		-

REPEAT CARDS 8-10 WITH LAST SET BLANK

INPUT (PLOT)

UNITS G(GM), C(CM), S(SEC), E(ERG), GA(GAUSS), P(POISE), O(OHM), M(METER), K(DEG K), A(ATM), D(DYNES), V(VOLTS), AC (ABCOULOMB)

CARD ONE (915.5X,E10.4)

MOVIE	1- 5	(0) no movie, (1) 16 or 35 mm movie (3) contour plot	-
IHIST	6-10	number of time history plots	-
ISPAT	11-15	number spatial distribution plots	-
IPARAM	16-20	number of parameter plots	-
ILINE	21-25	number of line elimination cards	-
ISC	26-30	(0) no shading, (-1) shading and/or contour mapping	-
IDET	31-35	(0) labels, (1) no labels, (3) punched cards of shade intensity, (5) 3-D plots	-
ISYM	36-40	(0) no symmetry, (1) mirror image about r-axis, (2) mirror image about z-axis	
IVEL	41-45	(0) no vectors, (1) vectors	
RPV	51-60	vectors plotted at inches/plot variable value	VAR

CARD TWO (1015)

ILOW	1- 5	minimum radial index to be plotted	-
JHIGH	6-10	maximum radial index to be plotted	-
JLOW	11-15	minimum axial index to be plotted	-
JHIGH	16-20	maximum axial index to be plotted	-
L1	21-25	if ILOW.NE.1, JLOW.NE.1, IHIGH.NE.KP2	-
L2	26-30	JHIGH.NE.JP2	-
L3	31-35	L1 = 1, L2 = KP2, L3 = 1, L4 = JP2	-
L4	36-40	otherwise L1 = L2 = L3 = L4 = 0	-
JPDEL	41-45	plot interval in axial direction	-
KPDEL	46-50	plot interval in radial direction	-

CARD THREE (4F10.4)

ZLOW	1-10	minimum axial coordinate	C
ZHIGH	11-20	maximum axial coordinate	C
XLOW	21-30	minimum radial coordinate	C
XHIGH	31-40	maximum radial coordinate	C

CARD FOUR (215)

IVX	1- 5	ordinate variable in vector plot (8 for velocity)	-
IVZ	6-10	abscissa variable in vector plot (7 for velocity)	-

CARD FOUR A (5I5)

IF IPART ≠ 0 READ:

IPLOW	1- 5	minimum ith particle cell location	-
IPHIGH	6-10	maximum "	-
JPLOW	11-15	minimum jth "	-
JPHIGH	16-20	maximum "	-
NPTS	21-25	number of cycles when new particles originate	-

CARD FIVE (6I5)

IHMIN	1- 5	minimum row for time history plots	-
IHMAX	6-10	maximum row for time history plots	-

JHMIN	11-15	minimum column for time history plots	-
JHMAX	16-20	maximum column for time history plots	-
MCODE	21-25	variable plotted (see table C.1)	-
MFRAME	26-30	number of time history plots per frame	-

CARD SIX (6I5)

ISMIN	1- 5	minimum row for line elimination	-
ISMAX	6-10	maximum row for line elimination	-
JSMIN	11-15	minimum column for line elimination	-
JSMAX	16-20	maximum column for line elimination	-
NCODE	21-25	(1) axial coordinate (horizontal) (2) radial coordinate (vertical)	-

CARD SEVEN (6I5) (At present, these values are overridden in GRIDS)

IZMIN	1- 5	minimum row for spatial distribution plots	-
IZMAX	6-10	maximum row for spatial distribution plots	-
JZMIN	11-15	minimum column for spatial distribution plots	-
JZMAX	16-20	maximum column for spatial distribution plots	-
MZODE	21-25	variable plotted (see table C.1)	-
MFRAME	26-30	number of spatial distribution plots per frame	-

CARD EIGHT (2E10.4,3(5X,I5))

Referring to Table C.1. Each cell (identified by indices I,J) has 36 variables stored on the disk by Subroutine GRAPH. These values are later employed to generate plots. At cycle intervals of NPLT, Subroutine GRAPH writes on disk unit 14. Later, when plotting is performed, Subroutines PLOTTE or GRIDS rewinds disk unit 14 and searches for specific plot data at various times and/or grid locations.

E1	1-10	minimum value to be shaded	VAR
E2	11-20	maximum value to be shaded	VAR
LI1	26-30	variable to be shaded (see table C.1)	-
LI2	36-40	(0) linear shade scale, (1) logarithmic scale	-
LI3	46-50	(0) shade only, (1) shade and velocity vectors	-

CARD NINE (5I5)

ISHIN	1- 5	minimum row to be shaded	-
ISHAX	6-10	maximum row to be shaded	-
JSHIN	11-15	minimum column to be shaded	-
JSHAX	16-20	maximum column to be shaded	-
NSHADE	21-25	shade intensity	-

CARD TEN (6I5)

IRMIN	1- 5	minimum row to be plotted on parametric plot	-
IRMAX	6-10	maximum row to be plotted on parametric plot	-
JRMIN	11-15	minimum column to be plotted on parametric plot	-
JRMAX	16-20	maximum column to be plotted on parametric plot	-
MPODE	21-25	variable plotted (see table C.1)	-

CARD ELEVEN (4F10.4,39X,I1)

TPLTMI	1-10	minimum plot time	S
TPLTMA	11-20	maximum plot time	S
TPLTDL	21-30	Time interval for spatial and time history plots	S
TPLTDE	31-40	time interval for grid plots	S
INUMM	80	(0) last plot set, otherwise (1)	-

Table C.1. Variable Assignments for Cell (I,J) for Subroutines Graph and RDPLT

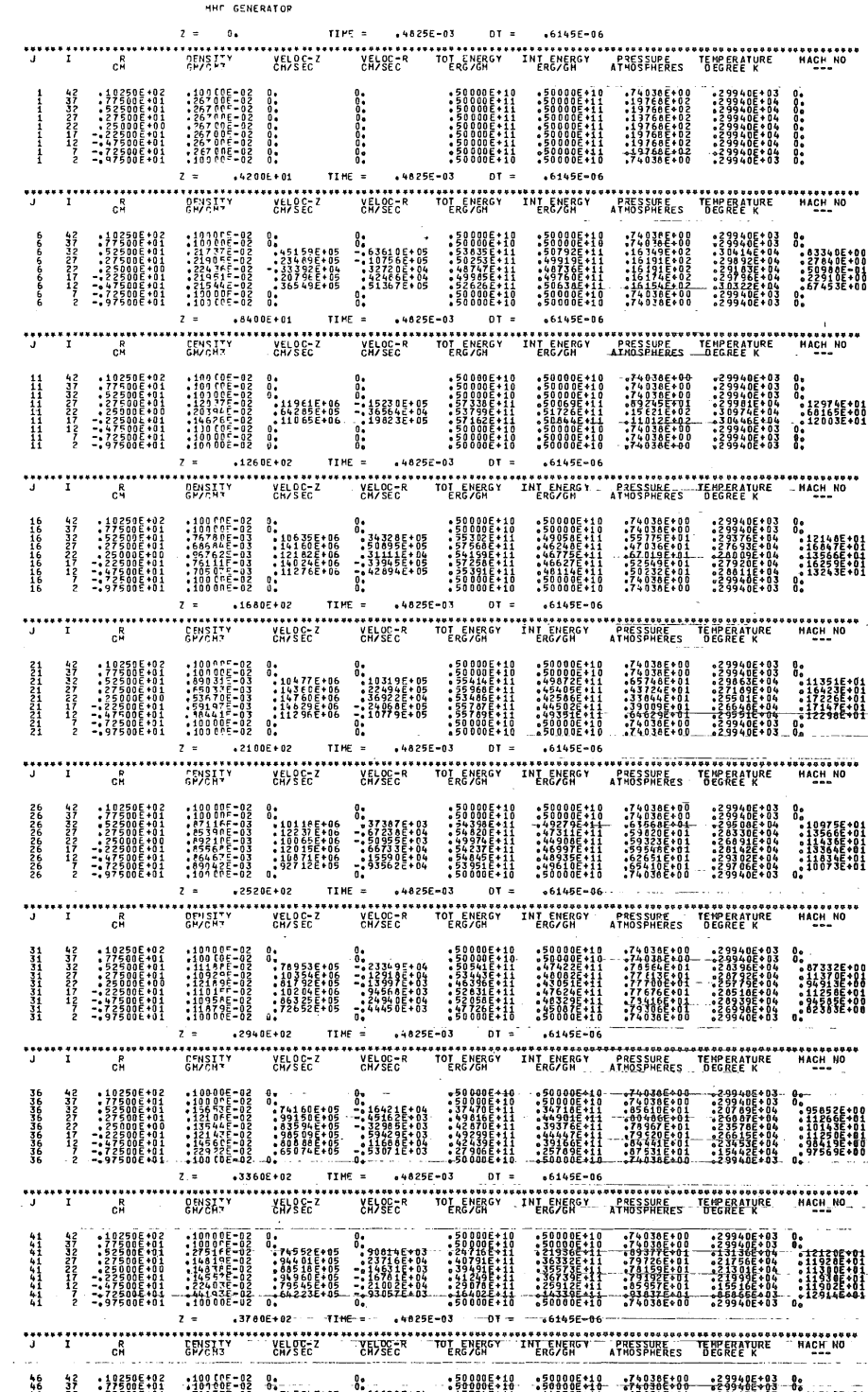
1	I	radial index	-
2	J	axial index	-
3	R	radial coordinate	C
4	Z	axial coordinate	C
5	DR	cell dimension in radial direction	C
6	DZ	cell dimension in axial direction	C
7	U	axial velocity	C/S
8	V	radial velocity	C/S
9	P	pressure	A
10	E	total energy/unit mass	E/G

11	INT	internal energy/unit mass	E/G
12	C	speed of sound	C/S
13	MACH	Mach number	-
14	RHO	density	G/C3
15	M	mass	G
16	BO	magnetic field - azimuthal direction	GA
17	TRR	stress - radial direction	D/C2
18	TZZ	stress - axial direction	D/C2
19	TOO	stress - azimuthal direction	D/C2
20	TRZ	shear	D/C2
21	ER	electric field - radial direction	GA·C/S
22	EZ	electric field - axial direction	GA·C/S
23	VISC	laminar viscosity	P
24	BR	magnetic field - radial direction	GA
25	BZ	magnetic field - axial direction	GA
26	JR	current - radial direction	$AC/S \cdot C^2$
27	JZ	current - axial direction	$AC/S \cdot C^2$
28	GAMMA	specific heat ratio	-
29	SIG	electrical conductivity	10^{-11}MHO
30	-	-	
31	TEMP	temperature	K
32	PHI	electrical potential	-
33	PSI	stream current function	-
34	BETA	hall parameter	-
35	COND	thermal conductivity	$GC/S^3 \cdot K$
36	VORT	vorticity	1/S

As an example of data input Figure C.2 depicts the input for a simple MHD generator. Output consists of a list of hydrodynamic (Figure C.3), viscous (Figure C.4), or electromagnetic (Figure C.5) variables for cells at intervals KPDEL and JPDEL. If NDIGPL is GT 0, then a digital plot (on-line printer) is produced (Figure C.6).

```
MHD GENERATOR

                                    IVIS    LRVZ
 KMAX      JMAX      IAXI      IPTSF     ISYM(1)   ISYM(2)   ISYM(3)   ISYM(4)   NVECT     NPDIM     MCALC     IRST      IOBQ      IPOT
  40        98         0         1         -1         0         1         1         2         1         6         1        17         1
    0.00      0.00
     RD        XD         RD        XD        RD        XD        RD        XD
     8.50      -.50       8.50      2.00      3.50      7.00      3.50      8.00
    3.90      8.50      4.25      9.00      4.85      10.00     5.55      12.00
    6.10      14.00     6.40      16.00     6.65      18.00     6.83      20.00
    7.00      22.00     7.00      70.00     4.50      74.00     4.50      75.00
    7.00      86.00
  SPACE     SPINSL    BASFP     DPOT      DVOLT     JPLMIN    JPLMAX
 .1000E+02 .5000E+01 .1000E+01 .1000E+01 .1000E+01    30        70
 NPRN      KPDEL     JPDEL     NPLOT     NPART     NMAX      NCYCLE
   1         5         5         1         1         1         0
    DZ0       DR0       XMIN      YMIN      MINDT     MAXDT     STAB      IZERO
 .8400E+00 .5000E+00 -.4200E+00 -.1050E+02  0.       .1000E+01 .5500E+00  0.
  RHO0      VZ        VP        E0        B0        BR        BZ        PHI
 .1000E-02  0.        0.       .5000E+10 .2000E+05  0.        0.        0.
  VISC0     PERM0     MW        ARFV
 .1000E+01 .1257E+02 .2900E+02  0.
          K1,J1,K2,J2,RHO0,VX,VY,E0,B0,BR0,BZ0,PHI0,VISC0,PERM0
            1  1  42  1  .2670E-02  0.       0.       .5000E+11 .2000E+05  0.       0.       0.
                       .1000E+01            .1257E+02
XXXX
```



MHD GENERATOR

Z = 0. TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
1	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
1	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
1	32	.52500E+01	.26700E-02	0.	0.	.50000E+11	.50000E+11	.19768E+02	.29940E+04	0.
1	27	.27500E+01	.26700E-02	0.	0.	.50000E+11	.50000E+11	.19768E+02	.29940E+04	0.
1	22	.25000E+00	.26700E-02	0.	0.	.50000E+11	.50000E+11	.19768E+02	.29940E+04	0.
1	17	-.22500E+01	.26700E-02	0.	0.	.50000E+11	.50000E+11	.19768E+02	.29940E+04	0.
1	12	-.47500E+01	.26700E-02	0.	0.	.50000E+11	.50000E+11	.19768E+02	.29940E+04	0.
1	7	-.72500E+01	.26700E-02	0.	0.	.50000E+11	.50000E+11	.19768E+02	.29940E+04	0.
1	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .4200E+01 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
6	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
6	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
6	32	.52500E+01	.21777E-02	-.45159E+05	-.63610E+05	.53435E+11	.50792E+11	.16149E+02	.30414E+04	.83340E+00
6	27	.27500E+01	.21908E-02	-.23469E+05	-.10766E+05	.50253E+11	.49919E+11	.16191E+02	.29892E+04	.27840E+00
6	22	.25000E+00	.22436E-02	-.33392E+04	.32720E+04	.48747E+11	.48736E+11	.16191E+02	.29183E+04	.50980E-01
6	17	-.22500E+01	.23196E-02	.20794E+05	.42466E+04	.49876E+11	.49176E+11	.16174E+02	.29298E+04	.72910E-01
6	12	-.47500E+01	.21544E-02	.36549E+05	.51367E+05	.52626E+11	.50636E+11	.16154E+02	.30322E+04	.67453E+00
6	7	-.72500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
6	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .8400E+01 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
11	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
11	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
11	32	.52500E+01	.10300E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
11	27	.27500E+01	.12917E-02	.11961E+06	-.15230E+05	.57338E+11	.50069E+11	.89245E+01	.29981E+04	.12974E+01
11	22	.25000E+00	.20394E-02	-.36564E+04	-.36564E+04	.53799E+11	.51726E+11	.15621E+02	.30974E+04	.68165E+00
11	17	-.22500E+01	.14626E-02	.11065E+06	-.19823E+05	.57162E+11	.50846E+11	.11012E+02	.31046E+04	.12003E+01
11	12	-.47500E+01	.11000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
11	7	-.72500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
11	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .1260E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
16	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
16	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
16	32	.52500E+01	.75780E-03	.10635E+06	.34328E+05	.35302E+11	.45055E+11	.55775E+01	.29376E+04	.12140E+01
16	27	.27500E+01	.68648E-03	.14160E+06	.50895E+05	.57568E+11	.46248E+11	.47036E+01	.27693E+04	.16847E+01
16	22	.25000E+00	.95762E-03	.12182E+06	.31111E+04	.54199E+11	.46775E+11	.62710E+01	.28000E+04	.13956E+01
16	17	-.22500E+01	.75111E-03	.14024E+06	-.33945E+05	.57258E+11	.46627E+11	.52549E+01	.27920E+04	.16259E+01
16	12	-.47500E+01	.70507E-03	.11276E+06	-.42894E+05	.55391E+11	.48114E+11	.50332E+01	.28811E+04	.13243E+01
16	7	-.72500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
16	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .1680E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
21	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
21	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
21	32	.52500E+01	.89035E-03	.10477E+06	.10319E+05	.35414E+11	.45872E+11	.65746E+01	.29863E+04	.11351E+01
21	27	.27500E+01	.85835E-03	.14356E+06	.22494E+05	.55968E+11	.45405E+11	.43724E+01	.27169E+04	.16423E+01
21	22	.25000E+00	.83670E-03	.12760E+06	.36922E+04	.53406E+11	.46255E+11	.43044E+01	.27501E+04	.14222E+01
21	17	-.22500E+01	.69197E-03	.14629E+06	-.24068E+05	.56707E+11	.44502E+11	.39009E+01	.26646E+04	.17147E+01
21	12	-.47500E+01	.71644E-03	.11296E+06	-.10779E+05	.55789E+11	.45391E+11	.64629E+01	.29951E+04	.12298E+01
21	7	-.72500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
21	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .2100E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
26	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
26	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
26	32	.52500E+01	.87114E-03	.10118E+06	-.37387E+03	.34398E+11	.49279E+11	.61668E+01	.29608E+04	.10975E+01
26	27	.27500E+01	.85199E-03	.14223E+06	-.26708E+05	.55820E+11	.47314E+11	.43130E+01	.27153E+04	.16356E+01
26	22	.25000E+00	.89219E-03	.13065E+06	-.50955E+03	.49976E+11	.44908E+11	.59323E+01	.28691E+04	.13436E+01
26	17	-.22500E+01	.85667E-03	.12019E+06	.66733E+04	.54237E+11	.46997E+11	.59548E+01	.28142E+04	.13364E+01
26	12	-.47500E+01	.96457E-03	.11499E+06	-.15590E+05	.54845E+11	.46935E+11	.42525E+01	.27303E+04	.11250E+01
26	7	-.72500E+01	.89042E-03	.92712E+05	-.93562E+04	.53951E+11	.45610E+11	.65410E+01	.29706E+04	.10073E+01
26	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .2520E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
31	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
31	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
31	32	.52500E+01	.11184E-02	.78953E+05	-.23349E+04	.50541E+11	.47422E+11	.79560E+01	.28396E+04	.87332E+00
31	27	.27500E+01	.10925E-02	.10335E+06	-.12919E+04	.51343E+11	.47443E+11	.77113E+01	.28207E+04	.11137E+01
31	22	.25000E+00	.12169E-02	.81792E+05	-.13997E+03	.46396E+11	.43051E+11	.77700E+01	.29175E+04	.94913E+00
31	17	-.22500E+01	.11011E-02	.10204E+06	.94568E+03	.52431E+11	.47624E+11	.77676E+01	.28516E+04	.11250E+01
31	12	-.47500E+01	.10954E-02	.86325E+05	.24944E+04	.52058E+11	.48329E+11	.73416E+01	.28615E+04	.94956E+00
31	7	-.72500E+01	.11479E-02	.72652E+05	-.44450E+03	.49772E+11	.45087E+11	.79306E+01	.29598E+04	.82383E+00
31	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .2940E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
36	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
36	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
36	32	.52500E+01	.15653E-02	.74160E+05	-.16421E+04	.37470E+11	.34071E+11	.54510E+01	.21089E+04	.95852E+00
36	27	.27500E+01	.12108E-02	.99158E+05	-.45162E+03	.49816E+11	.44901E+11	.80486E+01	.26087E+04	.11266E+01
36	22	.25000E+00	.13544E-02	.83594E+05	-.32985E+03	.48370E+11	.43976E+11	.78967E+01	.23578E+04	.10143E+01
36	17	-.22500E+01	.12142E-02	.98509E+05	.59429E+03	.49229E+11	.44447E+11	.79520E+01	.26615E+04	.11250E+01
36	12	-.47500E+01	.14566E-02	.80888E+05	-.11668E+04	.42439E+11	.39166E+11	.84461E+01	.23655E+04	.98419E+00
36	7	-.72500E+01	.12372E-02	.65074E+05	-.53071E+03	.47966E+11	.42778E+11	.87731E+01	.25942E+04	.97569E+00
36	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .3360E+02 TIME = .4825E-03 DT = .6145E-06

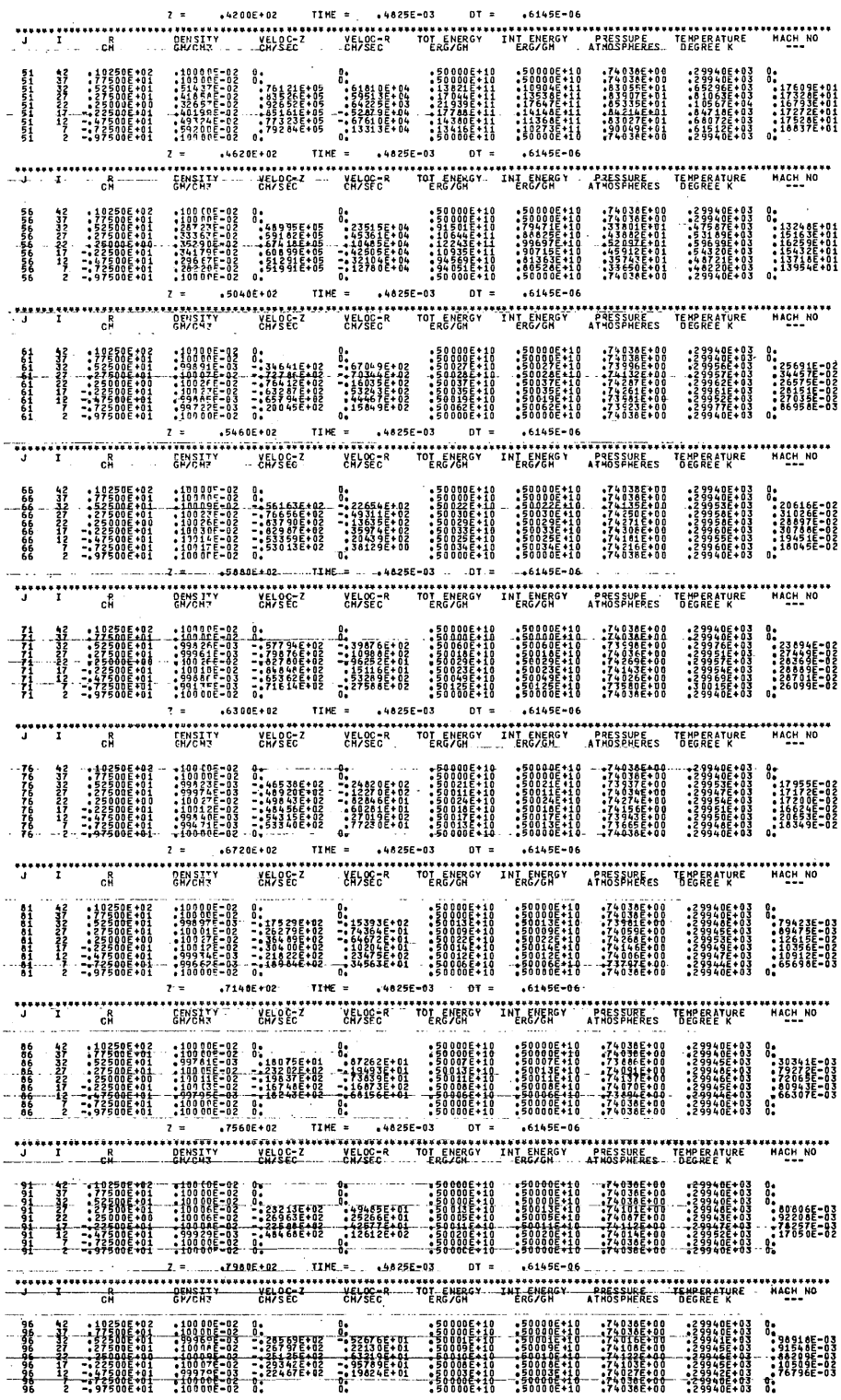
J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
41	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
41	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
41	32	.52500E+01	.27516E-02	.74552E+05	-.90014E+03	.26716E+11	.21939E+11	.38397E+01	.15136E+04	.12120E+01
41	27	.27500E+01	.13481E-02	.94401E+05	-.23716E+04	.40791E+11	.36332E+11	.79726E+01	.21756E+04	.11920E+01
41	22	.25000E+00	.14837E-02	.88518E+05	-.14651E+03	.39491E+11	.35573E+11	.79159E+01	.21101E+04	.11310E+01
41	17	-.22500E+01	.13455E-02	.98960E+05	-.16701E+04	.41248E+11	.36759E+11	.79192E+01	.21999E+04	.11920E+01
41	12	-.47500E+01	.22403E-02	.79545E+05	-.21002E+04	.29078E+11	.25912E+11	.85957E+01	.15516E+04	.11902E+01
41	7	-.72500E+01	.44142E-02	.64223E+05	-.93057E+03	.16402E+11	.14335E+11	.93617E+01	.85842E+03	.12914E+01
41	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .3780E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
46	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
46	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
46	32	.52500E+01	.38473E-02	.74524E+05	.66620E+04	.17731E+11	.14932E+11	.85951E+01	.89613E+03	.14742E+01
46	27	.27500E+01	.23139E-02	.89791E+05	.58435E+04	.27389E+11	.23437E+11	.99846E+01	.14079E+04	.13093E+01
46	22	.25000E+00	.18075E-02	.92123E+05	.11067E+04	.31075E+11	.26834E+11	.79339E+01	.17264E+04	.13063E+01
46	17	-.22500E+01	.31966E-02	.89526E+05	-.44222E+04	.20676E+11	.16468E+11	.80214E+01	.10476E+04	.13744E+01
46	12	-.47500E+01	.33386E-02	.77395E+05	-.81496E+04	.19605E+11	.16657E+11	.63582E+01	.10474E+04	.14519E+01
46	7	-.72500E+01	.57663E-02	.70303E+05	.12406E+04	.13937E+11	.11466E+11	.97900E+01	.68657E+03	.15808E+01
46	2	-.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

R(1) = RMIN + DRO/2

Figure C.3 Output Table, Hydrodynamic Variables



Z = .4200E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
51	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
51	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
51	32	.52500E+01	.51437E-02	.76121E+09	.61810E+04	.13621E+11	.11904E+11	.83055E+01	.65296E+03	.17609E+01
51	27	.27500E+01	.41824E-02	.83526E+05	.59513E+04	.17044E+11	.13570E+11	.83307E+01	.81063E+03	.17338E+01
51	22	.25000E+00	.32657E-02	.92652E+05	.64225E+03	.21939E+11	.17967E+11	.85335E+01	.11057E+04	.16773E+01
51	17	.22500E+01	.46199E-02	.85161E+05	.52879E+04	.17788E+11	.14140E+11	.84214E+01	.84710E+03	.17272E+01
51	12	.47500E+01	.49172E-02	.77237E+05	.67610E+04	.14380E+11	.11368E+11	.83027E+01	.68072E+03	.17529E+01
51	7	.72500E+01	.52200E-02	.79284E+05	.13313E+04	.11416E+11	.90049E+01	.80152E+03	.61512E+03	.16837E+01
51	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .4620E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
56	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
56	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
56	32	.52500E+01	.28723E-02	.48975E+05	.23515E+04	.91501E+10	.79471E+10	.33801E+01	.47587E+03	.13248E+01
56	27	.27500E+01	.33167E-02	.59182E+05	.45361E+04	.10644E+11	.86825E+10	.43082E+01	.53169E+03	.15163E+01
56	22	.25000E+00	.35290E-02	.67418E+05	.10485E+04	.12243E+11	.99697E+10	.52032E+01	.59699E+03	.16259E+01
56	17	.22500E+01	.34179E-02	.60899E+05	.42506E+04	.10935E+11	.90715E+10	.46912E+01	.54320E+03	.15432E+01
56	12	.47500E+01	.29617E-02	.52911E+05	.32110E+04	.94569E+10	.76138E+10	.35774E+01	.47212E+03	.14711E+01
56	7	.72500E+01	.28220E-02	.51991E+05	.12780E+04	.94051E+10	.80524E+10	.33650E+01	.44820E+03	.13954E+01
56	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .5040E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
61	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
61	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
61	32	.52500E+01	.69851E-03	.34641E+02	.67049E+02	.50027E+10	.50027E+10	.71996E+00	.21495E+03	.25691E-02
61	27	.27500E+01	.41024E-02	.27486E+02	.70344E+02	.50028E+10	.50028E+10	.74132E+00	.29957E+03	.34457E-02
61	22	.25000E+00	.10032E-02	.76412E+02	.16035E+02	.50037E+10	.50037E+10	.74267E+00	.29962E+03	.26575E-02
61	17	.22500E+01	.40977E-02	.48787E+02	.61341E+02	.50035E+10	.50035E+10	.74261E+00	.29960E+03	.26163E-02
61	12	.47500E+01	.40946E-03	.16279E+02	.14467E+02	.50019E+10	.50019E+10	.73991E+00	.29952E+03	.27038E-02
61	7	.72500E+01	.99722E-03	.20045E+02	.15849E+02	.50062E+10	.50062E+10	.73923E+00	.29977E+03	.86958E-03
61	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .5460E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
66	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
66	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
66	32	.52500E+01	.10000E-02	.56163E+02	.22654E+02	.50022E+10	.50022E+10	.74135E+00	.29953E+03	0.
66	27	.27500E+01	.10023E-02	.76666E+02	.49311E+02	.50030E+10	.50030E+10	.74250E+00	.29956E+03	.20616E-02
66	22	.25000E+00	.10026E-02	.63790E+02	.13635E+02	.50029E+10	.50029E+10	.74271E+00	.29958E+03	.31026E-02
66	17	.22500E+01	.10030E-02	.82907E+02	.39974E+02	.50033E+10	.50033E+10	.74308E+00	.29960E+03	.28857E-02
66	12	.47500E+01	.13711E-02	.53369E+02	.20439E+02	.50025E+10	.50025E+10	.74161E+00	.29955E+03	.30758E-02
66	7	.72500E+01	.10017E-02	.53013E+02	.36129E+00	.50034E+10	.50034E+10	.74216E+00	.29958E+03	.19451E-02
66	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	.18045E-02

Z = .5880E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
71	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
71	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
71	32	.52500E+01	.99422E-03	.57794E+02	.39876E+02	.50060E+10	.50060E+10	.71998E+00	.29976E+03	.23694E-02
71	27	.27500E+01	.99964E-03	.79876E+02	.10988E+02	.50016E+10	.50016E+10	.74036E+00	.29951E+03	.27449E-02
71	22	.25000E+00	.10056E-02	.67780E+02	.99625E+01	.50029E+10	.50029E+10	.74269E+00	.29957E+03	.26425E-02
71	17	.22500E+01	.10010E-02	.86848E+02	.15116E+01	.50023E+10	.50023E+10	.74143E+00	.29954E+03	.28889E-02
71	12	.47500E+01	.99868E-03	.65362E+02	.93289E+02	.50049E+10	.50049E+10	.74026E+00	.29969E+03	.28701E-02
71	7	.72500E+01	.99617E-03	.71614E+02	.27506E+02	.50015E+10	.50015E+10	.73881E+00	.29950E+03	.26095E-02
71	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .6300E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
76	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
76	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
76	32	.52500E+01	.99823E-03	.46536E+02	.24820E+02	.50021E+10	.50021E+10	.73937E+00	.29953E+03	.17955E-02
76	27	.27500E+01	.99937E-03	.48920E+02	.12270E+02	.50011E+10	.50011E+10	.74134E+00	.29947E+03	.17210E-02
76	22	.25000E+00	.10027E-02	.49843E+02	.62184E+01	.50024E+10	.50024E+10	.74274E+00	.29954E+03	.17210E-02
76	17	.22500E+01	.10012E-02	.48456E+02	.60281E+01	.50018E+10	.50018E+10	.74156E+00	.29951E+03	.16624E-02
76	12	.47500E+01	.99871E-03	.53340E+02	.27019E+02	.50017E+10	.50017E+10	.73943E+00	.29950E+03	.20653E-02
76	7	.72500E+01	.99671E-03	.53340E+02	.27230E+01	.50013E+10	.50013E+10	.73665E+00	.29948E+03	.18349E-02
76	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .6720E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
81	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
81	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
81	32	.52500E+01	.99897E-03	.17529E+02	.15393E+02	.50013E+10	.50013E+10	.73981E+00	.29948E+03	.79423E-03
81	27	.27500E+01	.10010E-02	.26279E+02	.73364E+01	.50013E+10	.50013E+10	.74059E+00	.29945E+03	.45947E-03
81	22	.25000E+00	.10037E-02	.35449E+02	.64672E+01	.50022E+10	.50022E+10	.74268E+00	.29953E+03	.12615E-02
81	17	.22500E+01	.10012E-02	.30400E+02	.38205E+01	.50014E+10	.50014E+10	.74145E+00	.29949E+03	.10356E-02
81	12	.47500E+01	.99974E-03	.21822E+02	.23475E+02	.50012E+10	.50012E+10	.73948E+00	.29947E+03	.10912E-02
81	7	.72500E+01	.99662E-03	.18984E+02	.34563E+01	.50006E+10	.50006E+10	.73707E+00	.29944E+03	.65698E-03
81	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .7140E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
86	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
86	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
86	32	.52500E+01	.99761E-03	.18075E+01	.87262E+01	.50013E+10	.50013E+10	.73986E+00	.29945E+03	.30341E-03
86	27	.27500E+01	.10005E-02	.23202E+02	.19493E+01	.50013E+10	.50013E+10	.74091E+00	.29946E+03	.79272E-03
86	22	.25000E+00	.10011E-02	.19637E+02	.73039E+01	.50011E+10	.50011E+10	.74137E+00	.29946E+03	.72065E-03
86	17	.22500E+01	.10010E-02	.16746E+02	.15073E+02	.50006E+10	.50006E+10	.74070E+00	.29943E+03	.80943E-03
86	12	.47500E+01	.99795E-03	.18243E+02	.68156E+01	.50006E+10	.50006E+10	.73804E+00	.29944E+03	.66307E-03
86	7	.72500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
86	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .7560E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
91	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
91	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
91	32	.52500E+01	.10006E-02	.23213E+02	.49485E+01	.50013E+10	.50013E+10	.74101E+00	.29948E+03	.80606E-03
91	27	.27500E+01	.10006E-02	.25263E+02	.25256E+01	.50005E+10	.50005E+10	.74067E+00	.29943E+03	.92208E-03
91	22	.25000E+00	.10008E-02	.22588E+02	.42877E+01	.50011E+10	.50011E+10	.74112E+00	.29947E+03	.78257E-03
91	17	.22500E+01	.10006E-02	.25263E+02	.12612E+02	.50020E+10	.50020E+10	.74014E+00	.29952E+03	.17050E-02
91	12	.47500E+01	.99929E-03	.18486E+02	.12612E+02	.50020E+10	.50020E+10	.74014E+00	.29952E+03	.17050E-02
91	7	.72500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
91	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Z = .7980E+02 TIME = .4825E-03 DT = .6145E-06

J	I	R CM	DENSITY GM/CM3	VELOC-Z CM/SEC	VELOC-R CM/SEC	TOT ENERGY ERG/GM	INT ENERGY ERG/GM	PRESSURE ATMOSPHERES	TEMPERATURE DEGREE K	MACH NO
96	42	.10250E+02	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
96	37	.77500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
96	32	.52500E+01	.99936E-03	.28569E+02	.52676E+01	.50001E+10	.50001E+10	.74010E+00	.29941E+03	.98916E-03
96	27	.27500E+01	.10008E-02	.26797E+02	.22130E+01	.50009E+10	.50009E+10	.74108E+00	.29945E+03	.91548E-03
96	22	.25000E+00	.10009E-02	.25126E+02	.63219E+01	.50010E+10	.50010E+10	.74122E+00	.29946E+03	.88209E-03
96	17	.22500E+01	.10007E-02	.29342E+02	.96789E+01	.50008E+10	.50008E+10	.74103E+00	.29945E+03	.10509E-02
96	12	.47500E+01	.99927E-03	.22467E+02	.19824E+01	.50003E+10	.50003E+10	.74027E+00	.29942E+03	.76796E-03
96	7	.72500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.
96	2	.97500E+01	.10000E-02	0.	0.	.50000E+10	.50000E+10	.74038E+00	.29940E+03	0.

Figure C.3 Continued

Z = 0. TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
1	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
1	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
1	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
1	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
1	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
1	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
1	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
1	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
1	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
1	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.

Z = .5000E+01 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
6	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
6	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.85753E+01
6	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.17313E+00
6	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.55979E-01
6	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.52491E-01
6	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.14413E+00
6	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40519E+00
6	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.90396E+01
6	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.39587E+05
6	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	

Z = .1000E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
11	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
11	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40921E+05
11	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.50256E+01
11	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.20915E+00
11	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.11471E-02
11	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.62472E-01
11	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.12216E+00
11	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.29955E+00
11	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.50636E+01
11	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40920E+05

Z = .1500E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
16	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
16	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40919E+05
16	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.75055E+01
16	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.75968E+00
16	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.42537E+00
16	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.63786E-01
16	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.28671E+00
16	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.55362E+00
16	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.70599E+01
16	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40918E+05

Z = .2000E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
21	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
21	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40898E+05
21	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.91480E+01
21	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.29173E+01
21	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.12468E+01
21	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.31500E-01
21	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.11420E+01
21	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.22209E+01
21	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.88644E+01
21	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40899E+05

Z = .2500E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
26	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
26	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40825E+05
26	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.20956E+02
26	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.54601E+01
26	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.19803E+01
26	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.13610E+01
26	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.11064E+01
26	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.14884E+01
26	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.20052E+02
26	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40813E+05

Z = .3000E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
31	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
31	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40934E+05
31	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.57116E+01
31	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.44303E-01
31	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.15358E+00
31	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.32956E-01
31	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.26453E-02
31	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.62577E+00
31	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.35229E+01
31	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40940E+05

Z = .3500E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
36	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
36	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40915E+05
36	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.16187E+01
36	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.10799E+01
36	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.37622E+00
36	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.12301E+00
36	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.15305E+00
36	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.74799E+00
36	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.70517E-01
36	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40912E+05

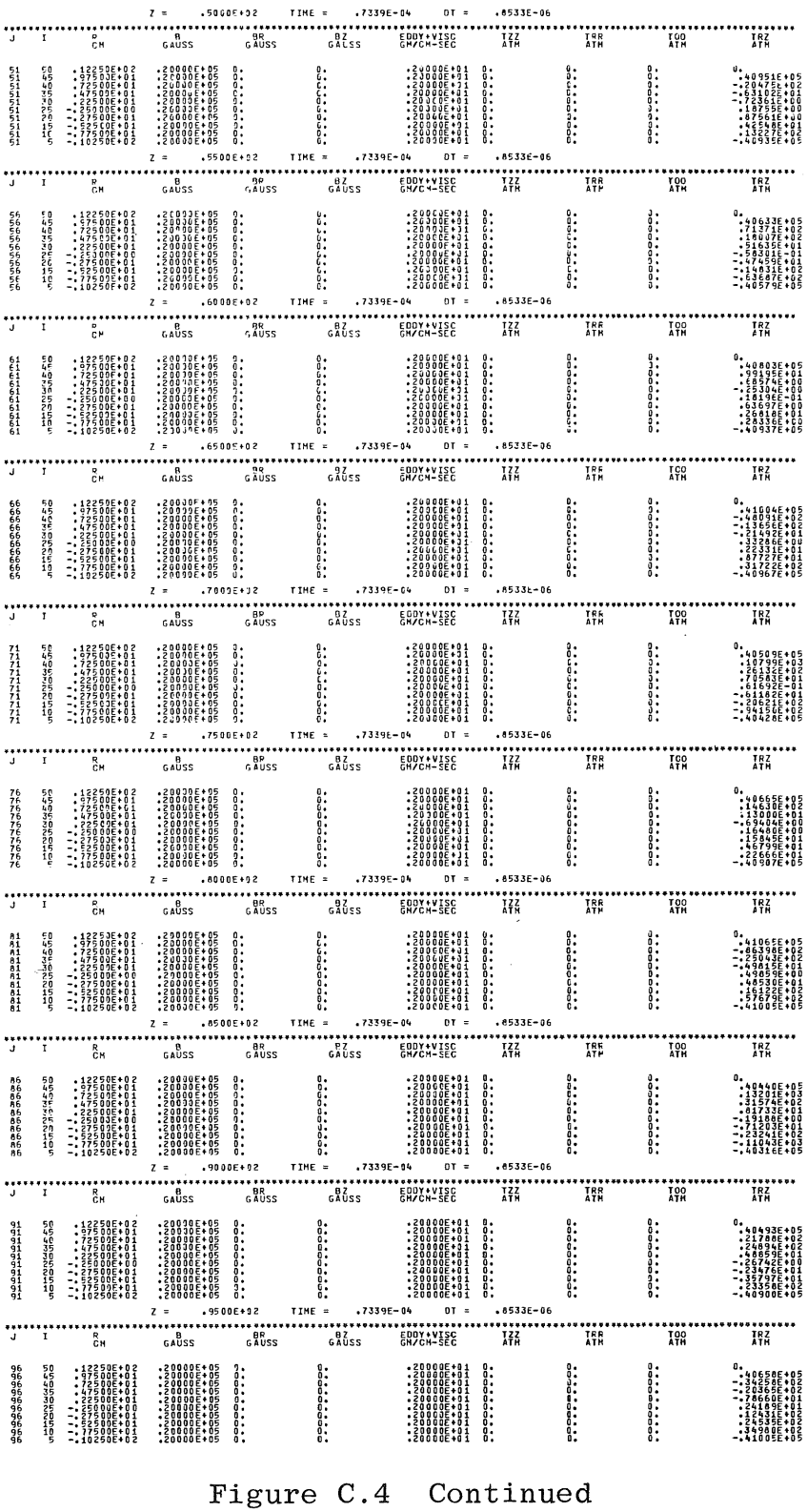
Z = .4000E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
41	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
41	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40739E+05
41	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.42806E+02
41	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.11954E+02
41	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.37243E+01
41	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.38169E-01
41	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.13795E+01
41	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.93570E+01
41	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.38720E+02
41	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40708E+05

Z = .4500E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY+VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
46	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
46	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40897E+05
46	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.68965E+01
46	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.63641E-01
46	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.80769E-01
46	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.16182E-01
46	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.30287E+00
46	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.10171E+01
46	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.14337E+01
46	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40955E+05

Figure C.4 Output Table, Viscous Variables



Z = .5000E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
51	50	.12250E+02	.20000E+05	0.	0.	.2W000E+01	0.	0.	0.	0.
51	45	.97500E+01	.20000E+05	0.	0.	.2J000E+01	0.	0.	0.	.40951E+05
51	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.20472E+02
51	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.81102E+01
51	30	.22500E+01	.20003E+05	0.	0.	.2003CE+01	0.	0.	0.	-.72361E+00
51	25	-.25000E+00	.20003E+05	0.	0.	.20300E+01	0.	0.	0.	.18758E+00
51	20	-.27500E+01	.20000E+05	0.	0.	.20046E+01	0.	0.	0.	.87561E+00
51	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.16249E+01
51	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.13557E+01
51	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40935E+05

Z = .5500E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
56	50	.12250E+02	.2C003E+05	0.	0.	.200C2E+01	0.	0.	0.	0.
56	45	.97500E+01	.20003E+05	0.	0.	.26300E+01	0.	0.	0.	.40633E+05
56	40	.72500E+01	.20000E+05	0.	0.	.20000E+31	0.	0.	0.	.71371E+02
56	35	.47503E+01	.20030E+05	0.	0.	.20000E+31	0.	0.	0.	.18007E+02
56	30	.22500E+01	.20000E+05	0.	0.	.20000E+31	0.	0.	0.	.51635E+01
56	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.58080E+00
56	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.47459E+01
56	15	-.52500E+01	.20000E+05	0.	0.	.2C300E+01	0.	0.	0.	-.11431E+02
56	10	-.77500E+01	.20095E+05	0.	0.	.20019E+31	0.	0.	0.	-.63687E+02
56	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40579E+05

Z = .6000E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
61	50	.12250E+02	.20013E+05	0.	0.	.20600E+01	0.	0.	0.	0.
61	45	.97500E+01	.20030E+05	0.	0.	.20000E+01	0.	0.	0.	.40803E+05
61	40	.72500E+01	.20030E+05	0.	0.	.20406E+01	0.	0.	0.	.99195E+01
61	35	.47530E+01	.20010E+05	0.	0.	.20000E+01	0.	0.	0.	.6857+E+00
61	30	.22500E+01	.20000E+05	0.	0.	.2W30E+31	0.	0.	0.	-.15300E+00
61	25	-.25000E+00	.20000E+05	0.	0.	.20000E+31	0.	0.	0.	.18196E-01
61	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.61692E+00
61	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.15519E+01
61	10	-.77500E+01	.20000E+05	0.	0.	.20030E+31	0.	0.	0.	.28336E+00
61	5	-.10250E+02	.2J0J0E+05	0.	0.	.200J0E+01	0.	0.	0.	-.40937E+05

Z = .6500E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
66	50	.12250E+02	.20030E+05	0.	0.	.2W000E+01	0.	0.	0.	0.
66	45	.97500E+01	.20030E+05	0.	0.	.20000E+01	0.	0.	0.	.41004E+05
66	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.48091E+02
66	35	.47500E+01	.20000E+05	0.	0.	.20000E+31	0.	0.	0.	-.13656E+02
66	30	.22500E+01	.20000E+05	0.	0.	.2W00E+31	0.	0.	0.	-.31495E+01
66	25	-.25000E+00	.20010E+05	0.	0.	.20000E+31	0.	0.	0.	.33286E+00
66	20	-.27500E+01	.20000E+05	0.	0.	.20466E+01	0.	0.	0.	.22339E+01
66	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.87727E+01
66	10	-.77500E+01	.20000E+05	0.	0.	.200W0E+01	0.	0.	0.	.31725E+02
66	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40967E+05

Z = .7000E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
71	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
71	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40509E+05
71	40	.72500E+01	.20003E+05	0.	0.	.20000E+01	0.	0.	0.	.10799E+03
71	35	.47500E+01	.20030E+05	0.	0.	.20000E+01	0.	0.	0.	.26136E+02
71	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.70583E+01
71	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.61693E+01
71	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.61182E+01
71	15	-.52563E+01	.20003E+05	0.	0.	.20006E+01	0.	0.	0.	-.20621E+02
71	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.49159E+02
71	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40428E+05

Z = .7500E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
76	50	.12250E+02	.20030E+05	0.	0.	.20000E+01	0.	0.	0.	0.
76	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40665E+05
76	40	.72500E+01	.20000E+05	0.	0.	.2W000E+01	0.	0.	0.	.14630E+03
76	35	.47500E+01	.20030E+05	0.	0.	.20700E+01	0.	0.	0.	.33139E+02
76	30	.22500E+01	.20000E+05	0.	0.	.20000E+31	0.	0.	0.	-.69404E+00
76	25	-.25000E+00	.20000E+05	0.	0.	.20000E+31	0.	0.	0.	.16480E+00
76	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.15845E+01
76	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.46799E+01
76	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.22866E+01
76	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40907E+05

Z = .8000E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
81	50	.12253E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
81	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.41065E+05
81	40	.72500E+01	.20000E+05	0.	0.	.2006WE+01	0.	0.	0.	-.86398E+02
81	35	.47500E+01	.20030E+05	0.	0.	.2006WE+31	0.	0.	0.	-.25043E+02
81	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.49815E+01
81	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.49859E+00
81	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.48530E+01
81	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.16122E+02
81	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.67679E+02
81	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.41005E+05

Z = .8500E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
A6	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
A6	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40440E+05
A6	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.13201E+03
A6	35	.47500E+01	.20003E+05	0.	0.	.20000E+01	0.	0.	0.	.31574E+02
A6	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.91733E+01
A6	25	-.25003E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.19188E+00
A6	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.71203E+01
A6	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.52541E+01
A6	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.11043E+03
A6	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40316E+05

Z = .9000E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
91	50	.12250E+02	.20030E+05	0.	0.	.20000E+01	0.	0.	0.	0.
91	45	.97500E+01	.20030E+05	0.	0.	.20000E+01	0.	0.	0.	.40493E+05
91	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.21788E+02
91	35	.47500E+01	.20030E+05	0.	0.	.20000E+31	0.	0.	0.	.24694E+02
91	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.14859E+01
91	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.26742E+00
91	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.23476E+01
91	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.35797E+01
91	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.23358E+01
91	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.40900E+05

Z = .9500E+02 TIME = .7339E-04 DT = .8533E-06

J	I	R CM	B GAUSS	BR GAUSS	BZ GAUSS	EDDY*VISC GM/CM-SEC	TZZ ATM	TRR ATM	TOO ATM	TRZ ATM
96	50	.12250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	0.
96	45	.97500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.40658E+05
96	40	.72500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.34258E+02
96	35	.47500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.22486E+02
96	30	.22500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.78668E+01
96	25	-.25000E+00	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.24189E+01
96	20	-.27500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.12931E+02
96	15	-.52500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.24539E+02
96	10	-.77500E+01	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	.34798E+02
96	5	-.10250E+02	.20000E+05	0.	0.	.20000E+01	0.	0.	0.	-.41005E+05

Figure C.4 Continued

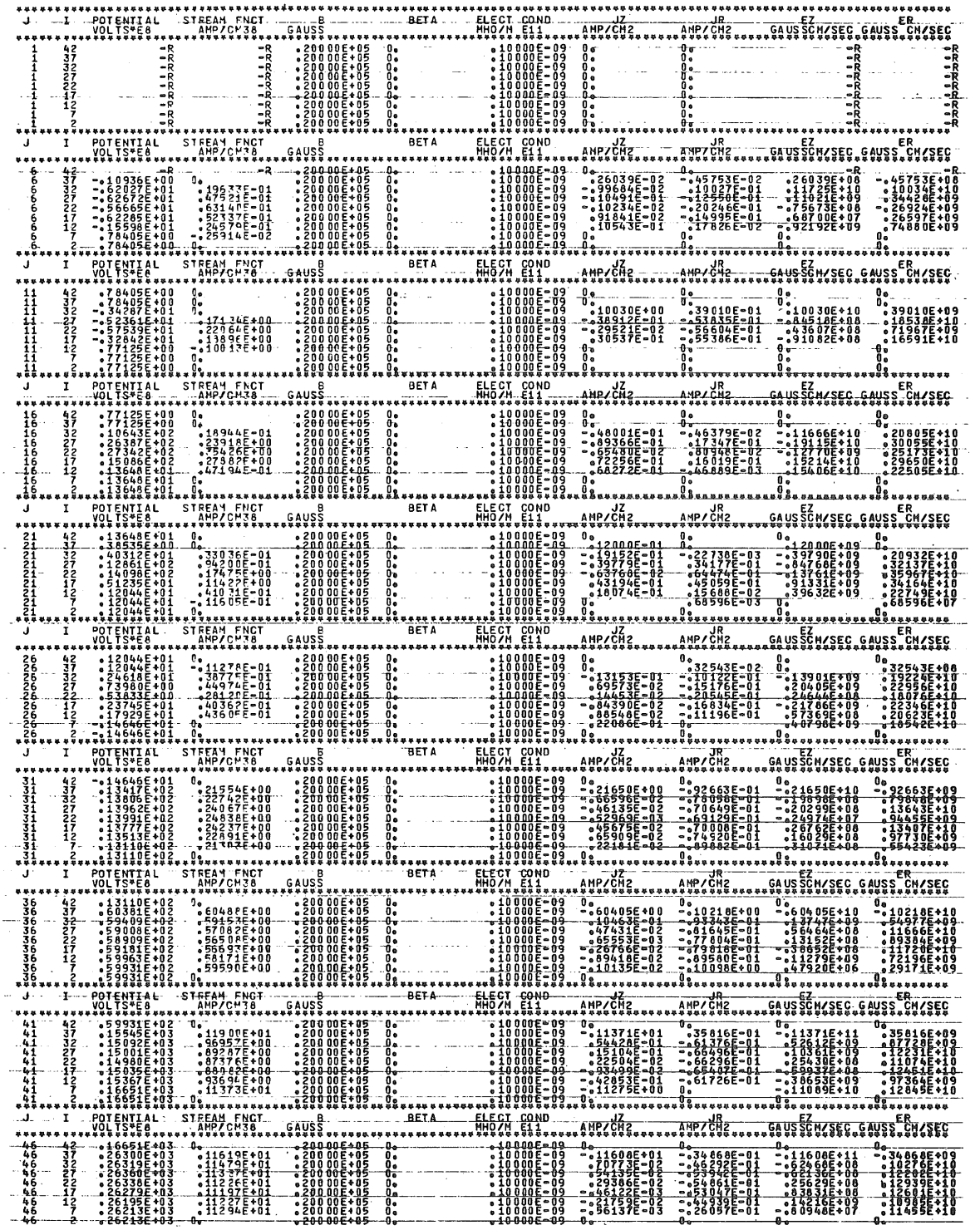
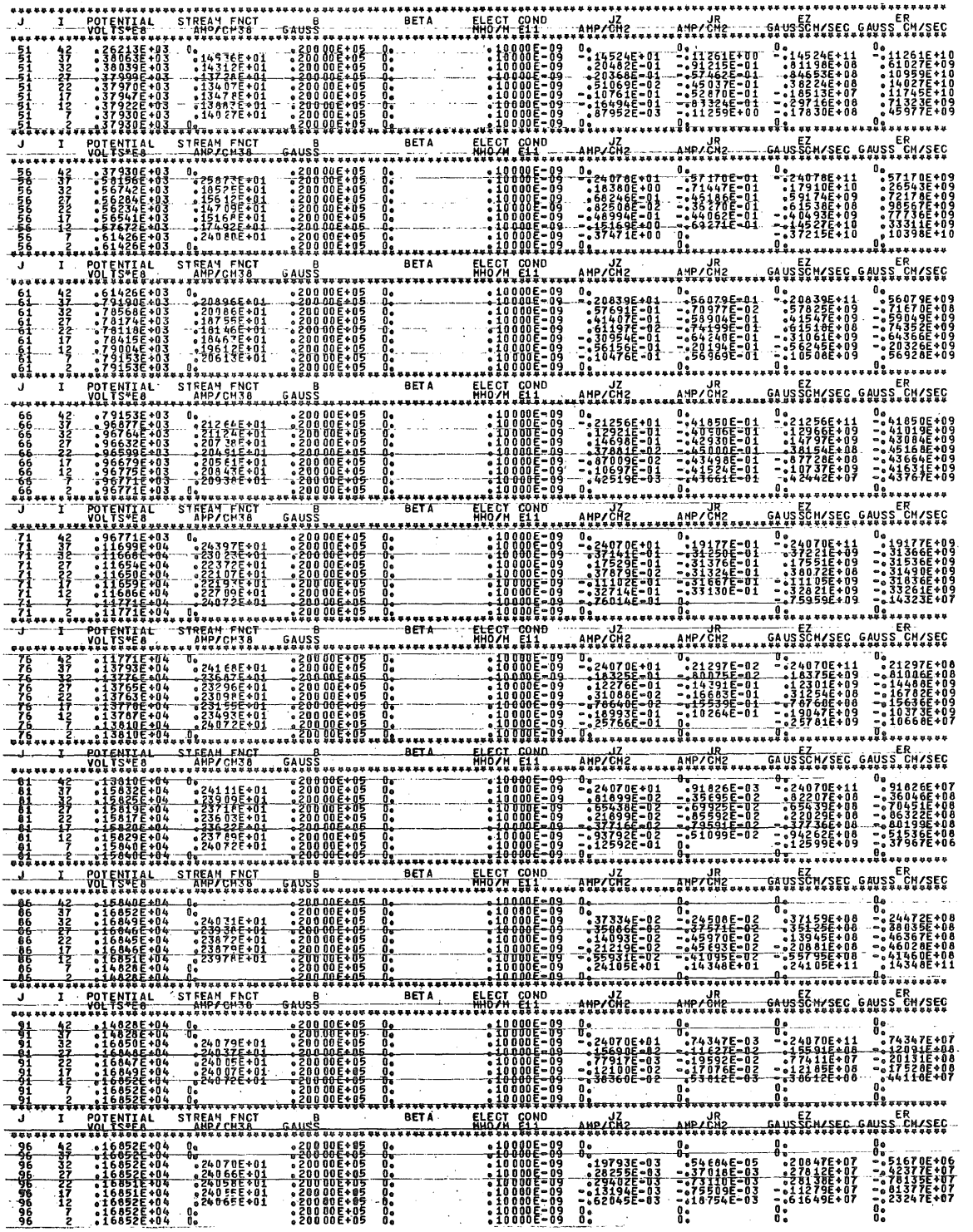


Figure C.5 Output Table, Electromagnetic Variables



J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
51	42	.26213E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
51	37	.38063E+03	.14576E+01	.20000E+05	0.	.10000E-09	-.14524E+01	-.11261E+00	-.14524E+11	-.11261E+10
51	32	.38039E+03	.14312E+01	.20000E+05	0.	.10000E-09	-.20482E-01	-.91215E-01	.81198E+08	.61027E+09
51	27	.37999E+03	.13728E+01	.20000E+05	0.	.10000E-09	-.20368E-01	-.57462E-01	.84653E+08	.10959E+10
51	22	.37970E+03	.13407E+01	.20000E+05	0.	.10000E-09	-.51069E-02	-.45037E-01	.36224E+08	.14027E+10
51	17	.37947E+03	.13478E+01	.20000E+05	0.	.10000E-09	-.10761E-01	-.52870E-01	-.18513E+07	.11745E+10
51	12	.37922E+03	.13887E+01	.20000E+05	0.	.10000E-09	-.16494E-01	-.83324E-01	-.29716E+08	.71323E+09
51	7	.37930E+03	.14027E+01	.20000E+05	0.	.10000E-09	-.87952E-03	-.11259E+00	-.17830E+08	.45977E+09
51	2	.37930E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
56	42	.37930E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
56	37	.51896E+03	.25877E+01	.20000E+05	0.	.10000E-09	-.24078E+01	-.57170E-01	-.24078E+11	-.57170E+09
56	32	.56742E+03	.18525E+01	.20000E+05	0.	.10000E-09	-.16380E+00	-.71447E-01	.17910E+10	.26543E+09
56	27	.56284E+03	.15612E+01	.20000E+05	0.	.10000E-09	-.68246E-01	-.46186E-01	.59174E+09	.72178E+09
56	22	.56234E+03	.14709E+01	.20000E+05	0.	.10000E-09	-.82508E-02	-.36170E-01	.61538E+08	.98567E+09
56	17	.56541E+03	.15167E+01	.20000E+05	0.	.10000E-09	-.48999E-01	-.45493E-01	-.14493E+09	.77736E+09
56	12	.56722E+03	.17492E+01	.20000E+05	0.	.10000E-09	-.15169E+00	-.69271E-01	-.14527E+10	.33311E+09
56	7	.61426E+03	.24088E+01	.20000E+05	0.	.10000E-09	-.37471E+00	0.	-.37215E+10	.10398E+10
56	2	.61426E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
61	42	.61426E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
61	37	.79190E+03	.20896E+01	.20000E+05	0.	.10000E-09	-.20839E+01	-.56079E-01	-.20839E+11	-.56079E+09
61	32	.78568E+03	.20086E+01	.20000E+05	0.	.10000E-09	.57693E-01	-.78977E-02	.57825E+09	-.71670E+08
61	27	.78174E+03	.18756E+01	.20000E+05	0.	.10000E-09	.44407E-01	-.59304E-01	.41647E+09	-.59049E+09
61	22	.78110E+03	.18146E+01	.20000E+05	0.	.10000E-09	.61197E-02	-.74199E-01	.61518E+08	-.74352E+09
61	17	.78415E+03	.18467E+01	.20000E+05	0.	.10000E-09	-.30954E-01	-.64240E-01	-.31061E+09	-.64366E+09
61	12	.79004E+03	.19612E+01	.20000E+05	0.	.10000E-09	-.56156E-01	-.20194E-01	-.56245E+09	-.20326E+09
61	7	.79153E+03	.20613E+01	.20000E+05	0.	.10000E-09	-.10476E-01	.56969E-01	-.10508E+09	.56928E+09
61	2	.79153E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
66	42	.79153E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
66	37	.96877E+03	.21264E+01	.20000E+05	0.	.10000E-09	-.21256E+01	-.41850E-01	-.21256E+11	-.41850E+09
66	32	.96764E+03	.21124E+01	.20000E+05	0.	.10000E-09	.12921E-01	-.40106E-01	.12966E+09	-.41019E+09
66	27	.96632E+03	.20738E+01	.20000E+05	0.	.10000E-09	.14698E-01	-.42930E-01	.14797E+09	-.43084E+09
66	22	.96599E+03	.20491E+01	.20000E+05	0.	.10000E-09	.37881E-02	-.45100E-01	.38154E+08	-.45168E+09
66	17	.96679E+03	.20561E+01	.20000E+05	0.	.10000E-09	-.87009E-02	-.43498E-01	-.87728E+08	-.43664E+09
66	12	.96775E+03	.20843E+01	.20000E+05	0.	.10000E-09	.10697E-01	-.41524E-01	.10737E+09	-.41631E+09
66	7	.96771E+03	.20938E+01	.20000E+05	0.	.10000E-09	.42519E-03	-.43661E-01	.42442E+07	-.43767E+09
66	2	.96771E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
71	42	.96771E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
71	37	.11699E+04	.24397E+01	.20000E+05	0.	.10000E-09	-.24070E+01	-.19177E-01	-.24070E+11	-.19177E+09
71	32	.11668E+04	.23023E+01	.20000E+05	0.	.10000E-09	.37144E-01	-.31250E-01	.37221E+09	-.31366E+09
71	27	.11654E+04	.22372E+01	.20000E+05	0.	.10000E-09	.17529E-01	-.31376E-01	.17551E+09	-.31536E+09
71	22	.11650E+04	.22107E+01	.20000E+05	0.	.10000E-09	.37879E-02	-.31324E-01	.38072E+08	-.31490E+09
71	17	.11659E+04	.22194E+01	.20000E+05	0.	.10000E-09	-.11102E-01	-.31667E-01	-.11105E+09	-.31836E+09
71	12	.11686E+04	.22709E+01	.20000E+05	0.	.10000E-09	-.32714E-01	-.33130E-01	-.32821E+09	-.33261E+09
71	7	.11771E+04	.24072E+01	.20000E+05	0.	.10000E-09	-.76014E-01	0.	-.75959E+09	-.14323E+07
71	2	.11771E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
76	42	.11771E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
76	37	.13793E+04	.24168E+01	.20000E+05	0.	.10000E-09	-.24070E+01	-.21297E-02	-.24070E+11	-.21297E+08
76	32	.13776E+04	.23607E+01	.20000E+05	0.	.10000E-09	-.18325E-01	-.80775E-02	-.18375E+09	-.81046E+08
76	27	.13765E+04	.23296E+01	.20000E+05	0.	.10000E-09	.12276E-01	-.14791E-01	.12301E+09	-.14848E+09
76	22	.13763E+04	.23098E+01	.20000E+05	0.	.10000E-09	-.31088E-02	-.16683E-01	-.31254E+08	-.16782E+09
76	17	.13770E+04	.23159E+01	.20000E+05	0.	.10000E-09	-.76640E-02	-.15539E-01	-.77560E+08	-.15636E+09
76	12	.13787E+04	.23493E+01	.20000E+05	0.	.10000E-09	-.16993E-01	-.10264E-01	-.19047E+09	-.10373E+09
76	7	.13810E+04	.24072E+01	.20000E+05	0.	.10000E-09	-.25766E-01	0.	-.25781E+09	-.10668E+07
76	2	.13810E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
81	42	.13810E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
81	37	.15832E+04	.24111E+01	.20000E+05	0.	.10000E-09	-.24070E+01	.91826E-03	-.24070E+11	.91826E+07
81	32	.15825E+04	.23909E+01	.20000E+05	0.	.10000E-09	.81999E-02	-.55855E-02	.82076E+08	-.56046E+08
81	27	.15819E+04	.23717E+01	.20000E+05	0.	.10000E-09	.65436E-02	-.69925E-02	.65439E+08	-.70451E+08
81	22	.15817E+04	.23603E+01	.20000E+05	0.	.10000E-09	.21699E-02	-.85592E-02	.22029E+08	-.86322E+08
81	17	.15820E+04	.23622E+01	.20000E+05	0.	.10000E-09	-.37716E-02	-.79591E-02	-.37736E+08	-.80199E+08
81	12	.15829E+04	.23789E+01	.20000E+05	0.	.10000E-09	-.93792E-02	-.51099E-02	-.94262E+08	-.51536E+08
81	7	.15840E+04	.24072E+01	.20000E+05	0.	.10000E-09	.12592E-01	0.	-.12599E+09	-.37967E+06
81	2	.15840E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
86	42	.15840E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
86	37	.16852E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
86	32	.16849E+04	.24031E+01	.20000E+05	0.	.10000E-09	.37334E-02	-.24508E-02	.37159E+08	-.24472E+08
86	27	.16846E+04	.23938E+01	.20000E+05	0.	.10000E-09	.35066E-02	-.37571E-02	.35125E+08	-.38035E+08
86	22	.16845E+04	.23872E+01	.20000E+05	0.	.10000E-09	.14093E-02	-.45970E-02	.13945E+08	-.46367E+08
86	17	.16846E+04	.23879E+01	.20000E+05	0.	.10000E-09	-.21219E-02	-.45693E-02	-.20881E+08	-.46028E+08
86	12	.16851E+04	.23997E+01	.20000E+05	0.	.10000E-09	-.55931E-02	-.41095E-02	-.55795E+08	-.41460E+08
86	7	.14828E+04	0.	.20000E+05	0.	.10000E-09	.24105E+01	.14348E+01	.24105E+11	.14348E+11
86	2	.14828E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
91	42	.14828E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
91	37	.14828E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
91	32	.16850E+04	.24079E+01	.20000E+05	0.	.10000E-09	-.24070E+01	.74347E-03	-.24070E+11	.74347E+07
91	27	.16848E+04	.24037E+01	.20000E+05	0.	.10000E-09	.15690E-02	-.11627E-02	.15691E+08	-.12091E+08
91	22	.16847E+04	.24015E+01	.20000E+05	0.	.10000E-09	.77917E-03	-.19592E-02	.77411E+07	-.20131E+08
91	17	.16849E+04	.24027E+01	.20000E+05	0.	.10000E-09	-.12100E-02	-.17076E-02	-.12105E+08	-.17528E+08
91	12	.16852E+04	.24072E+01	.20000E+05	0.	.10000E-09	-.30360E-02	.53412E-03	-.30612E+08	.44110E+07
91	7	.16852E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
91	2	.16852E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL VOLTS*E8	STREAM FNCT AMP/CM38	B GAUSS	BETA	ELECT COND MHO/M E11	JZ AMP/CM2	JR AMP/CM2	EZ GAUSS	ER CM/SEC
96	42	.16852E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
96	37	.16852E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
96	32	.16852E+04	.24070E+01	.20000E+05	0.	.10000E-09	.19793E-03	.54664E-05	.20847E+07	-.51670E+06
96	27	.16852E+04	.24066E+01	.20000E+05	0.	.10000E-09	.28255E-03	-.37018E-03	.28612E+07	-.42377E+07
96	22	.16851E+04	.24059E+01	.20000E+05	0.	.10000E-09	.29412E-03	-.73170E-03	.28138E+07	-.78135E+07
96	17	.16851E+04	.24055E+01	.20000E+05	0.	.10000E-09	-.13194E-03	-.79509E-03	-.11279E+07	-.81377E+07
96	12	.16852E+04	.24065E+01	.20000E+05	0.	.10000E-09	-.62045E-03	-.18754E-03	-.61649E+07	-.23247E+07
96	7	.16852E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
96	2	.16852E+04	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

Figure C.5 Continued

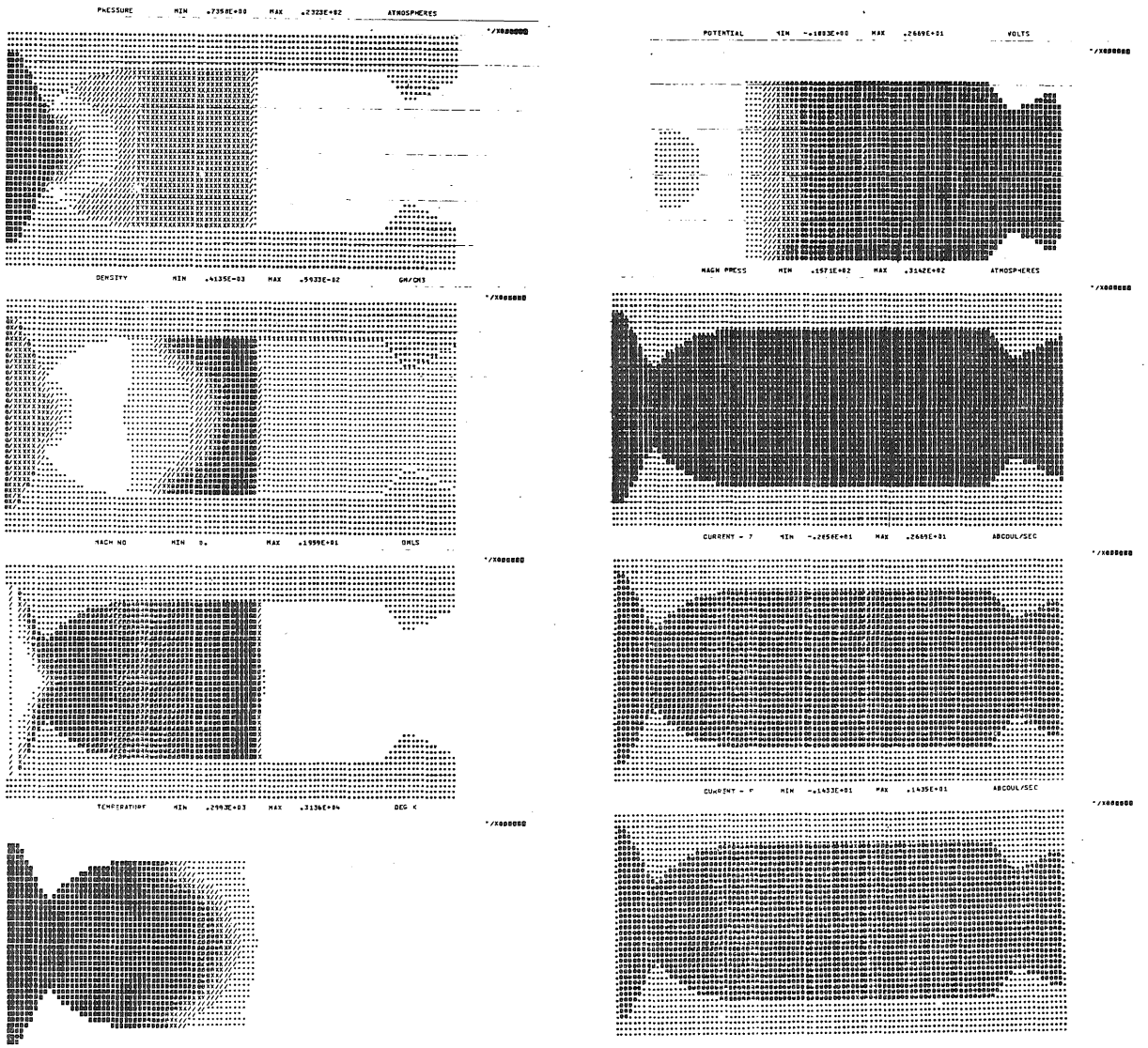


Figure C.6 Digital Plots

Computer graphics for this program consist of the following:

(1) Time Histories

(2) Spatial Distributions

(3) Vectors

(4) Contour Mapping

(5) Grey-Level Scaling

(6) Trace Particles

(7) Three-Dimensional Perspectives

Animation is easily achieved by generating sixteen or thirty-five mm motion pictures from a sequence of individual frames of the above plots. Sections 3, 4 and 5 of this report contain numerous examples of the graphics which facilitates the analysis of problems under investigation. A brief discussion of each plot follows:

(1) TIME HISTORIES

At a given cell or group of cells, it may be desirable to trace the time history of certain variables such as pressure (Table C.1, Variable (9)). As an example, consider the following input (Fig. C.7), at cell I = 11, J = 3, pressure is plotted as a function of time.

TPLTDL is normally input as zero, but may be assigned a specified time interval at which time histories are plotted. In the event TPLTDL is zero, NPLOT (hydro input), which specifies the cycle interval at which data is stored to be plotted later, controls the number of time data points. If TPLTMA, TPLTDE or TPLTDL are greater than T (e.g. 1.0), the last hydro cycle time, then TPLTMA, TPLTDE and TPLTDL are set equal to T.

(2) SPATIAL DISTRIBUTIONS

The question often arises as to how certain variables vary in either the axial or radial direction. Consider the MHD generator problem where it is desirable to find the location of a discontinuity along the centerline (Fig. C.8)

ISMIN	ISMAX	JSMIN	JSMAX	MCODE
11	11	1	69	9
11	11	1	69	13
11	11	1	69	14

at cells I = 11, J = 1, 69, pressure (9), Mach number (13) and temperature (31) are plotted. The axial distribution of pressure, Mach number and temperature reveal the location of this discontinuity at a specific time.

```
MOVIE    IHIST    ISPAT    IPARAM   ILINE     ISC      IDET     ISYM     IVEL    RPV      IPART
  0        1        0        0        2        0        0        0        0   0.           0
ILOW     IHIGH     JLOW     JHIGH    JPDEL    KPDEL
  1       22        1       69        1        1
ZLOW          ZHIGH          XLOW          XHIGH
.1000E+01    .8100E+02   -.5200E+02    .2800E+02
IHMIN IHMAX JHMIN JHMAX PCODE MFRAME
  11     11     3      3      9      0
ISMIN ISMAX JSMIN JSMAX NCODE
   1     22     1     69     1
   1     22     1     69     2
TPLTMI        TLPTMA         TPLTDE
0.            .3882E-03   0.
```

Input on Card as 1.0 (>.3882E-03) and Program Redefines to this Value

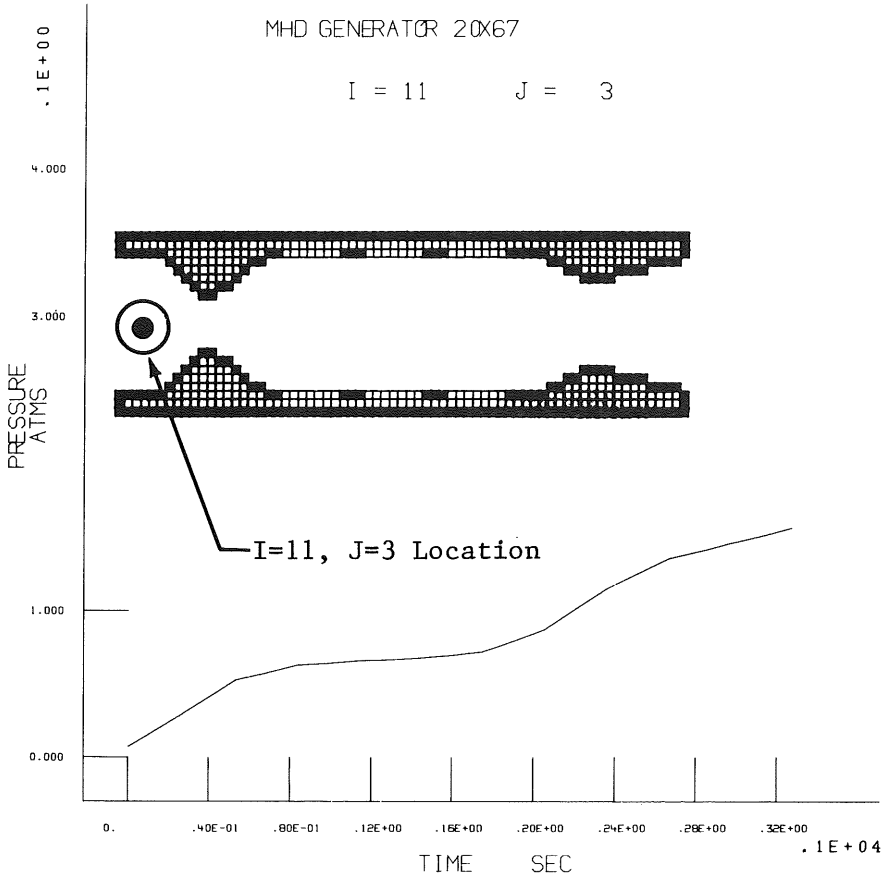


Figure C.7 Time History

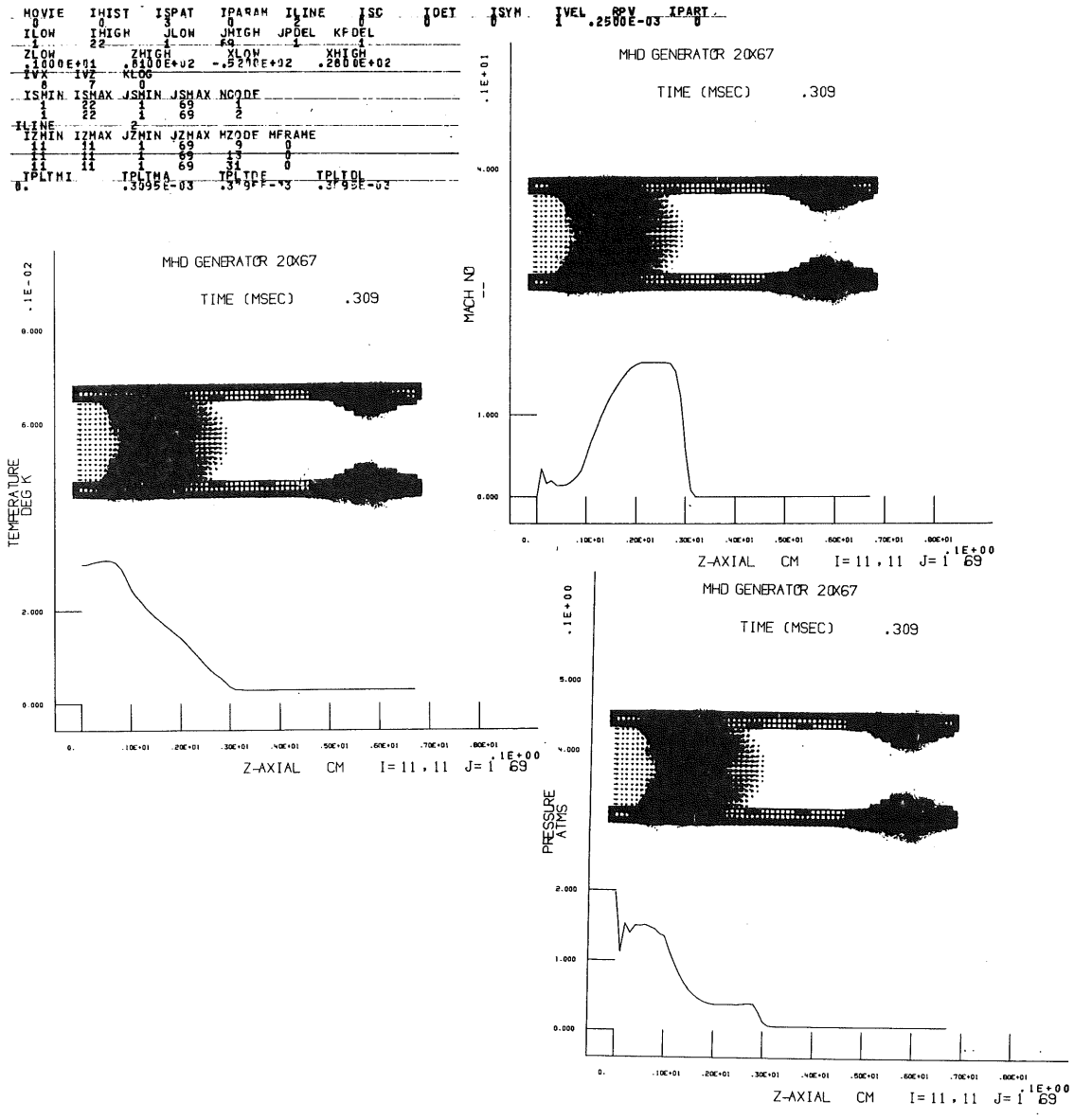


Figure C.8 Spatial Distributions

(3) VECTORS

Vector plots provide a useful tool in examining the magnitude and direction of such variables as the velocity and electric currents or fields.

Given radial and axial vector components at each cell, arrows are drawn with a direction = $\tan^{-1}$ (radial component/axial component) and a magnitude proportional to the square root of the sum of squares of both components. Thus, velocity vectors have a direction = $\tan^{-1}$ (V/U) and magnitude proportional to $\sqrt{\bar{v}^2}$. The proportional constant RPV was originally meant to represent "rasters per velocity" (cm/sec), where there are 1023 rasters along each axis. If the average velocity is 20000 cm/sec, in order to space vectors without overlapping, RPV is set at approximately 0.001 so that the length of each arrow is approximately 20000 x 0.001 or 20 rasters. Forty or fifty arrows would then comfortably fit in each direction.

As an example of a vector plot, Figure C.9 depicts velocity and current density vectors.

```
IVEL = 1

RPV = 0.001                 RPV = 100.0
(velocity)                  (current)

IVX = 8 radial velocity     IVX = 26 radial current
IVZ = 7 axial velocity      IVZ = 27 axial current

JPDEL = 1
KPDEL = 1
```

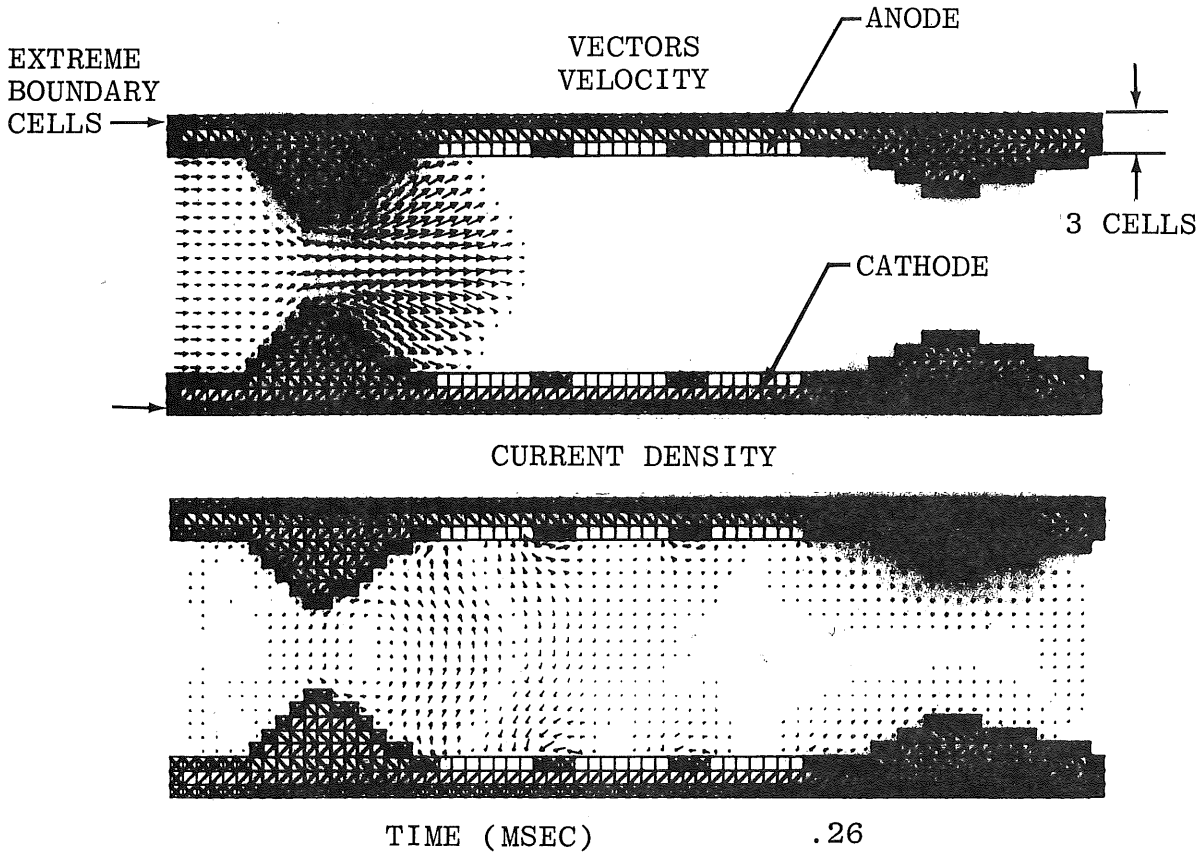
arrows will be drawn at every cell in the axial and radial directions.

(4) CONTOUR MAPPING

Contours are lines of a constant property value. Contour maps illustrate regions of weak or strong gradients and coupled with shade intensity plots or 3-D plots, depict the direction of gradients. Sections (3), (4), and (5) of this report contain numerous examples of contour maps. As a simple example, consider the following input:

```
MOVIE = 3
ISC = -1
E1 = Minimum Contour Value
E2 = Maximum Contour Value
LI1 = Contour Variable (Table C.1)
```

Forty contours (fixed in program) will be drawn whose equidistant values lie between E1 and E2. The contour map for this problem is shown in Fig. C.10. (Input data will be shown later in Fig. C.18).



Note: Cells defining the electrode-pairs (anode/cathode) must not lie on the extreme boundary. In the example above, they lie 2 cells below this boundary. Simply make RD values at least 1½ "DR0's" less than R_{max} [= R(1) + (KP2 - 1) * DR0] (See Fig. C.2, page 215).

Figure C.9 Vectors

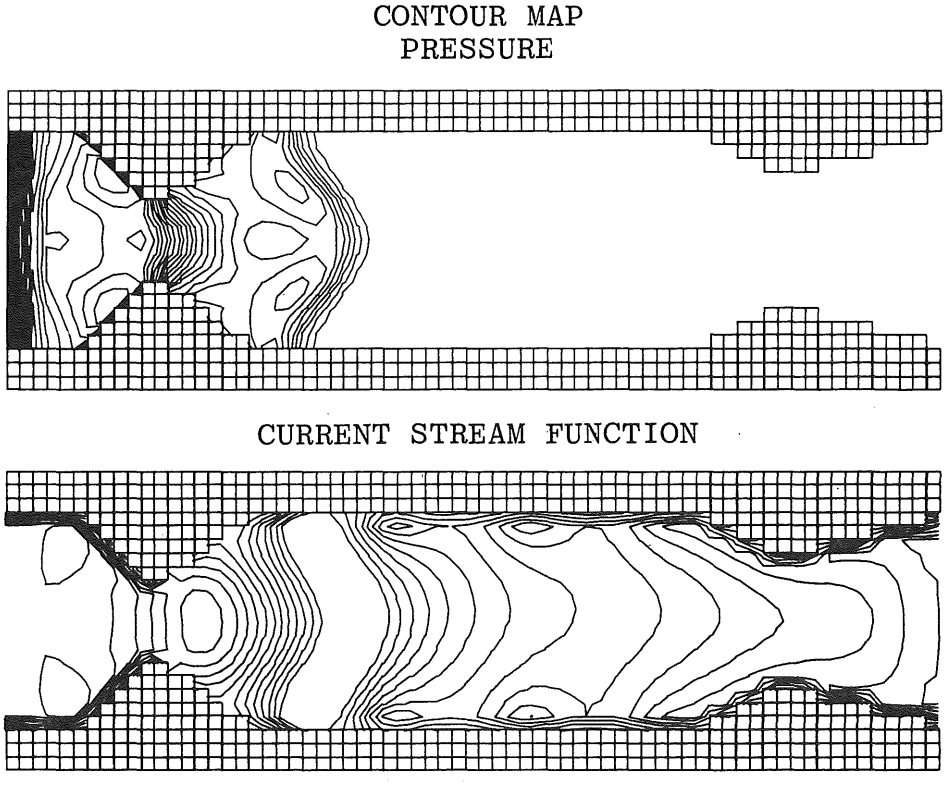


Figure C.10 Contours

(5) GREY-LEVEL SCALING

Grey-level scaling plots are generated by representing each contour region of a contour map by a shade intensity or grey level. The higher the value of the contour parameter in the contour region, the darker or more intense the shading. The advantage to this type of scaling is that it provides a rapid means for analyzing large amounts of data in one concise plot. Contour plots suffer from the difficulty in labelling different contours especially in rapidly changing regions, whereas the combination of shade and contour mapping does so routinely.

The same data for contour mapping is used for shading with the exception that

MOVIE = 0

Figure C.11 reveals a shade/contour map.

(6) TRACE PARTICLES

Trace particles as the name implies, traces or labels the trajectory of a prescribed number of particles in a dynamic media. Initially, particles are defined at specified locations (cells) and assume the velocity and coordinates of that cell. After a series of time increments, the particles move from cell to cell always assuming the velocity and coordinate values of the cell that it lies in. Observing the motion of these particles in time, the motion of the fluid may be more clearly understood.

Figure C.12 illustrates tracer particles and Mach contours.

(7) THREE-DIMENSIONAL PLOTS

The data for creating contours:

Grid Coordinates (X,Y)
Variable Z (e.g., P, M, T, etc.)

can be used just as easily to create a three-dimensional plot. The advantage of the 3-D graph is that gradient directions become apparent (peaks, valleys) whereas they are not so with contours. Numerous 3-D plots are shown in Figures C.13 through C.17. The only difference between contour data input and 3-D data input is that IDET = 5 in the latter case.

In summary, a number of plots have been described which aid in the analysis of computer results. The following graphs further illustrate their contributions.

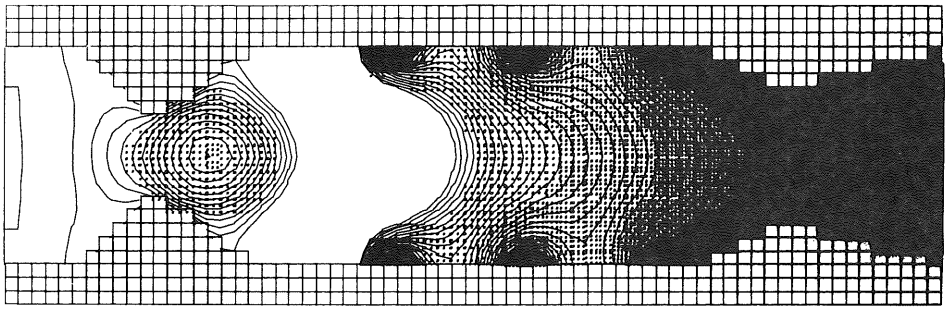


Figure C.11 Grey-Level Scaling

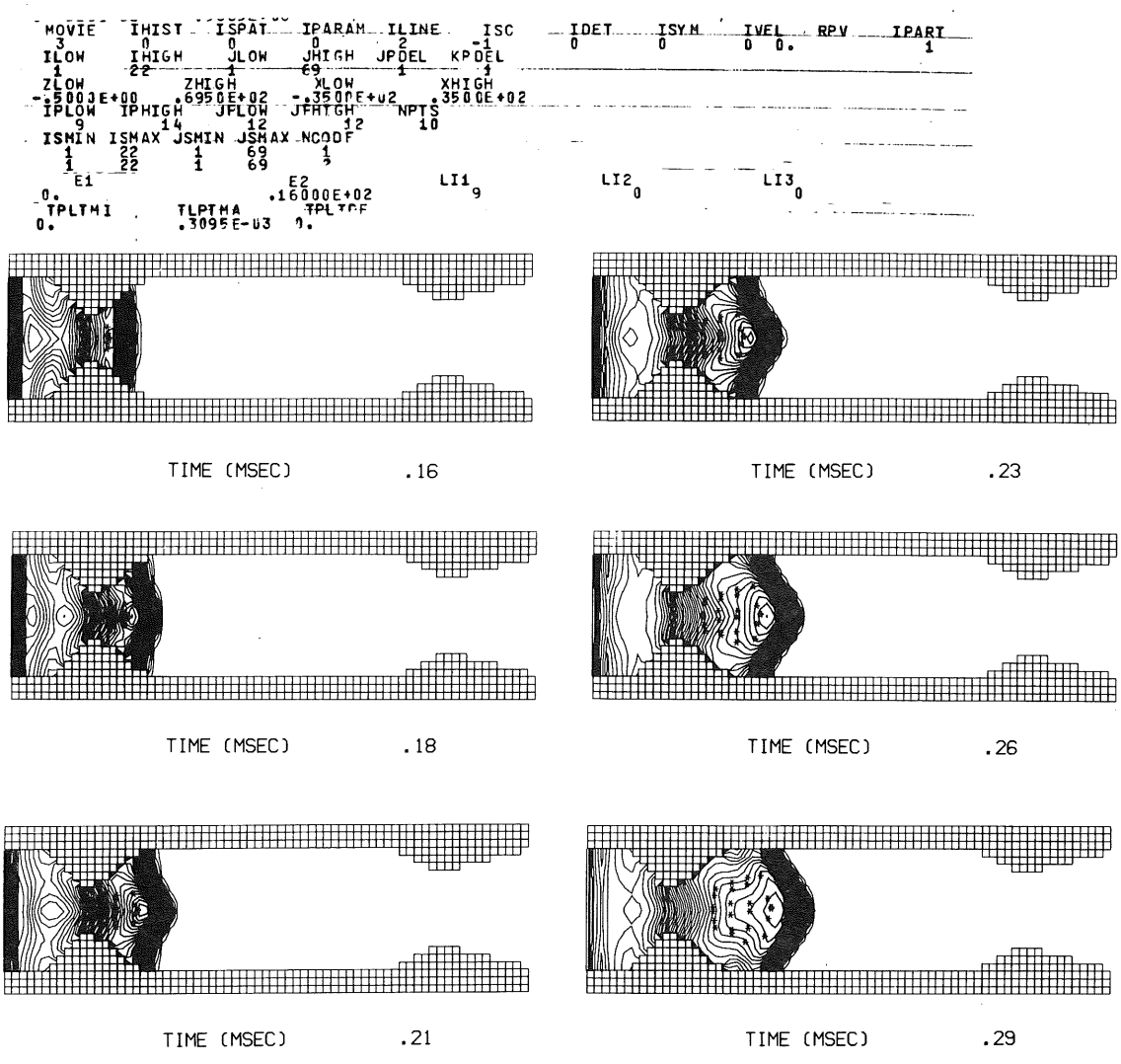


Figure C.12 Trace Particles

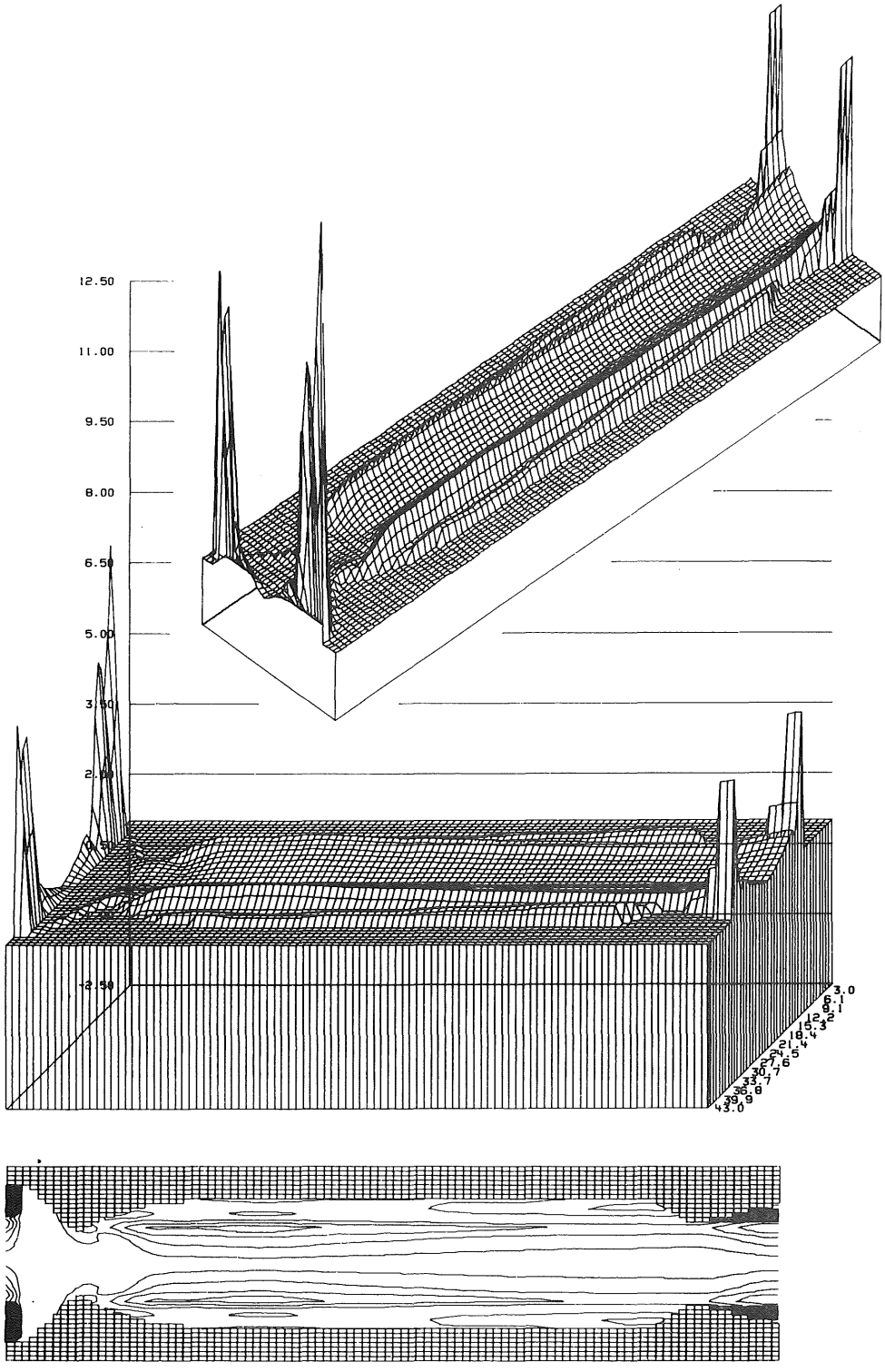


Figure C.13 Three-Dimensional Electric Potential

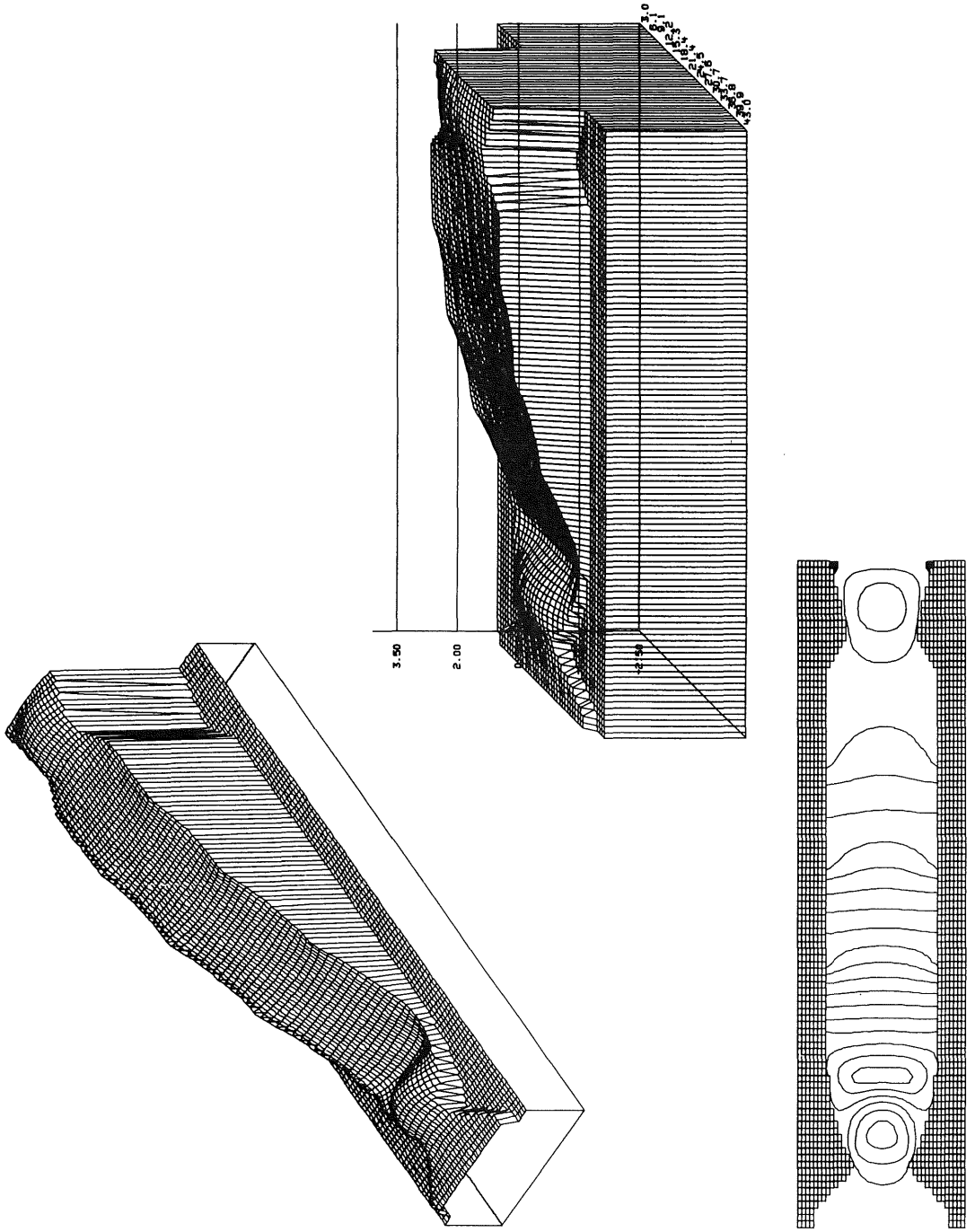


Figure C.14 Three-Dimensional Current Stream Function

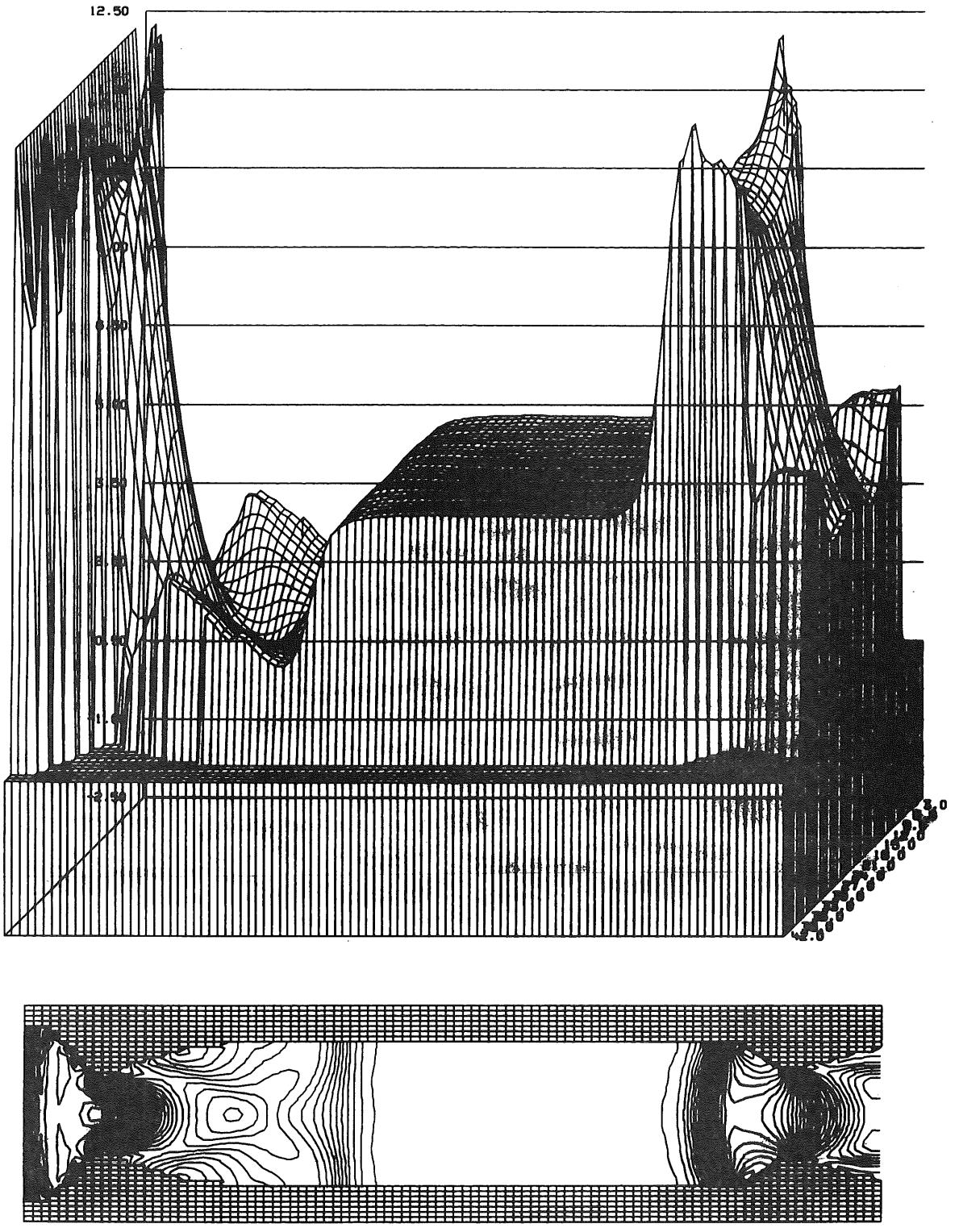


Figure C.15 Three-Dimensional Pressure

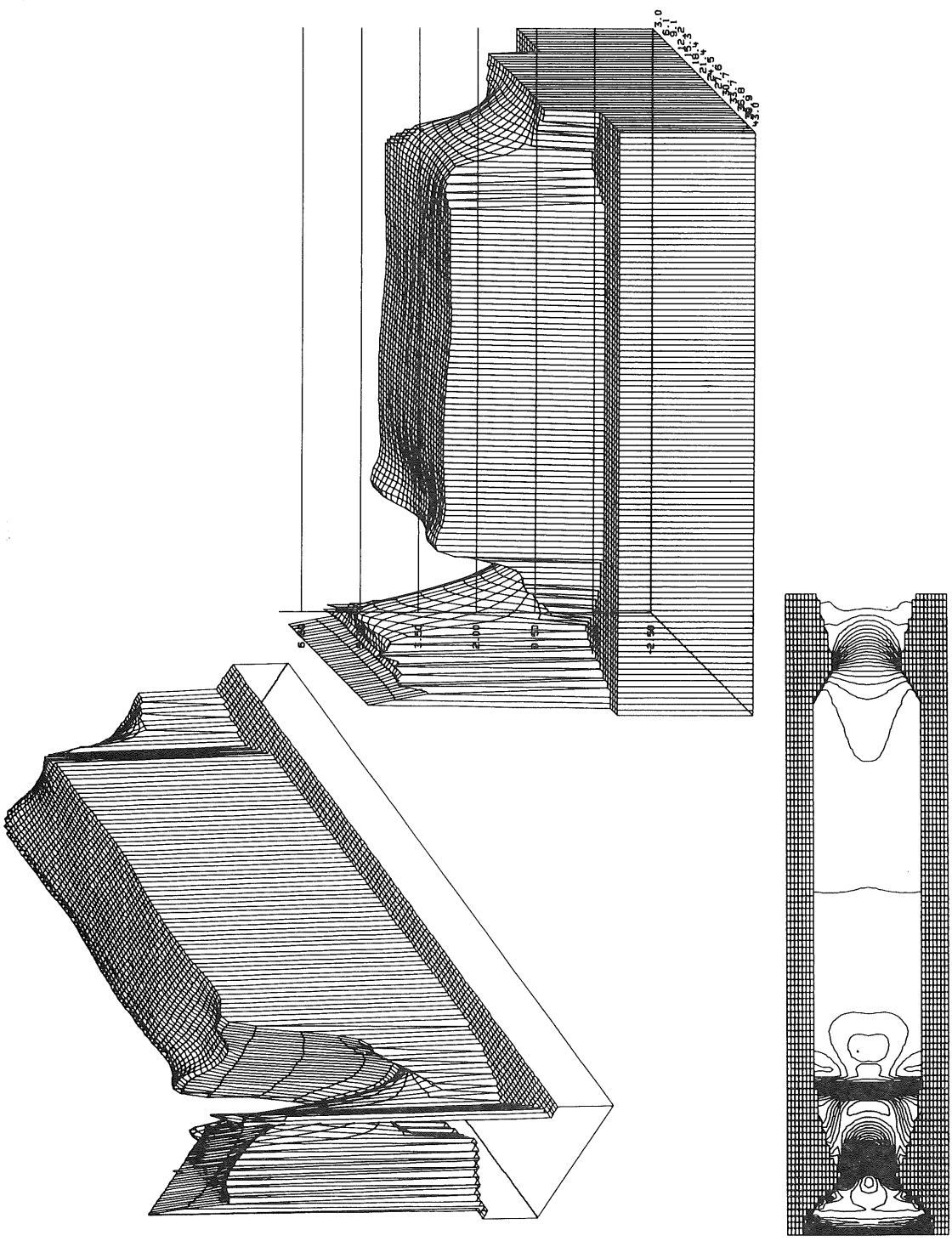


Figure C.16 Three-Dimensional Mach Number

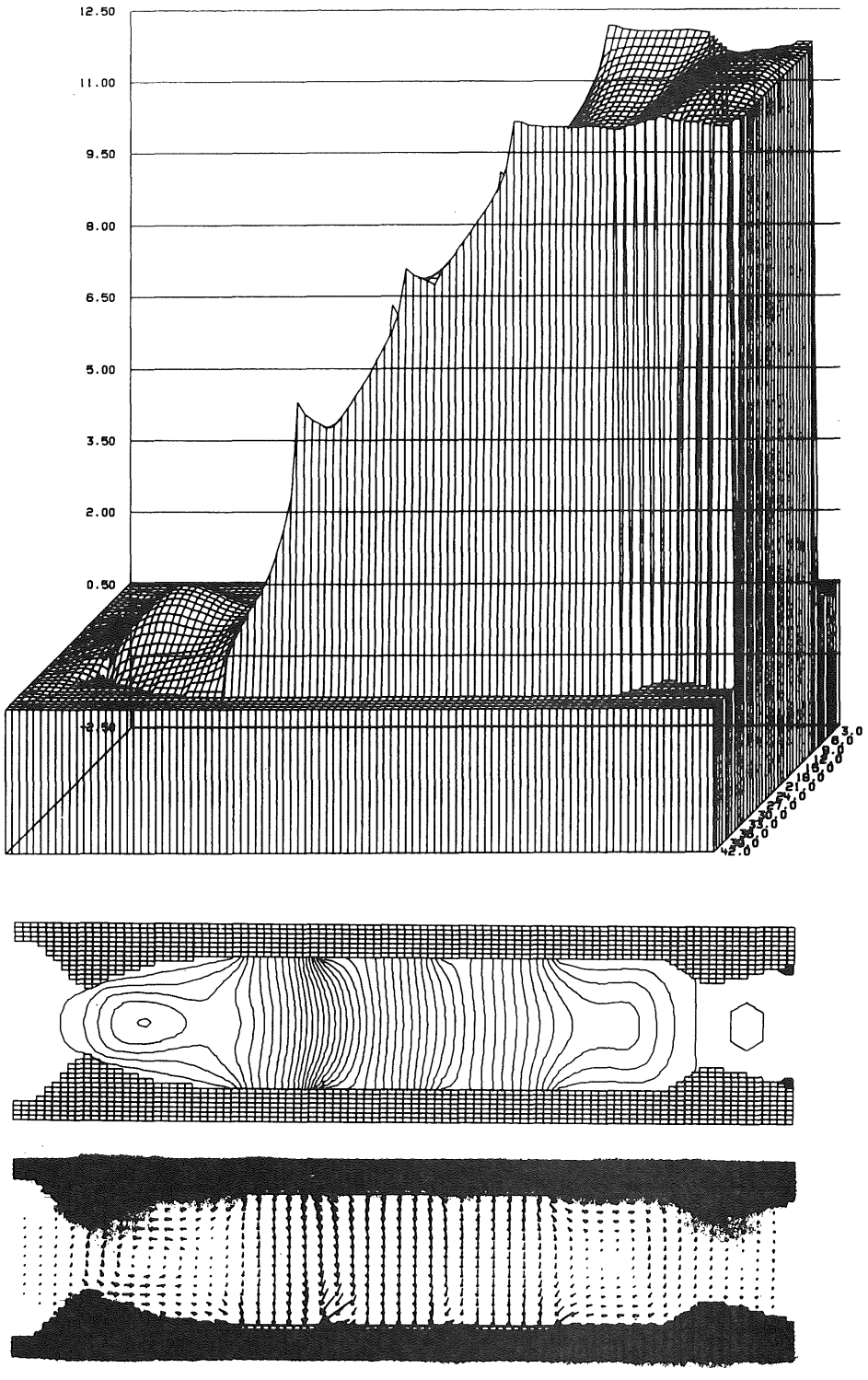
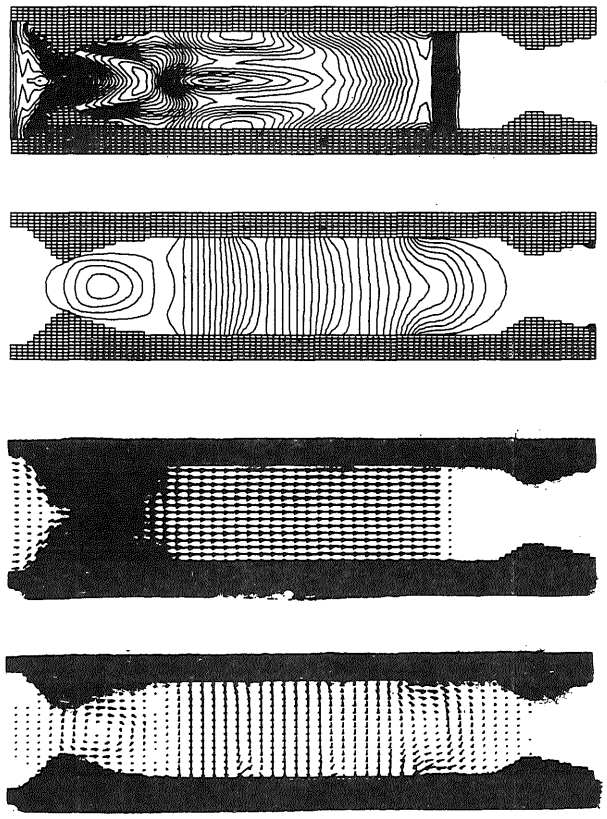


Figure C.17 3-D and Contour Plots of ψ



```
MOVIE   IHIST   ISPAT   IPARAM  ILINE    ISC      IDET     ISYM     IVEL   RPV      IPART
  1       0       0       0       2       -1       5        0        0   0.           0
ILOW    IHIGH    JLOW   JHIGH   JPDEL   KPDEL
  1      42       1     100       1       1
ZLOW          ZHIGH          XLOW          XHIGH
-.5000E+00    .8250E+02   -.4150E+02    .4150E+02
ISMIN ISMAX JSMIN JSMAX NCODE
  1     42    1   100     1
  1     42    1   100     2
          E1                    E2                  LI1              LI2              LI3
      0.                    .25000E+01    13          0                0
TPLTMI          TPLTMA          TPLTDE          TPLTDL
0.              .2504E-02       .2504E-02       .2504E-02
```

```
MOVIE   IHIST   ISPAT   IPARAM  ILINE    ISC      IDET     ISYM     IVEL   RPV      IPART
  3       0       0       0       2       -1       5        0        0   0.           0
ILOW    IHIGH    JLOW   JHIGH   JPDEL   KPDEL
  1      42       1     100       1       1
ZLOW          ZHIGH          XLOW          XHIGH
-.5000E+00    .8250E+02   -.4150E+02    .4150E+02
ISMIN ISMAX JSMIN JSMAX NCODE
  1     42    1   100     1
  1     42    1   100     2
          E1                    E2                  LI1              LI2              LI3
     -.20000E+00              .25000E+01    33          0                0
TPLTMI          TPLTMA          TPLTDE          TPLTDL
0.              .2504E-02       .2504E-02       .2504E-02
```

```
MOVIE   IHIST   ISPAT   IPARAM  ILINE    ISC      IDET     ISYM     IVEL   RPV      IPART
  0       0       0       0       2       0        1        0        1   .2500E-03    0
ILOW    IHIGH    JLOW   JHIGH   JPDEL   KPDEL
  1      42       1     100       2       2
ZLOW          ZHIGH          XLOW          XHIGH
-.5000E+00    .8250E+02   -.4150E+02    .4150E+02
IVX   IVZ   KLOG
  8     7     0
ISMIN ISMAX JSMIN JSMAX NCODE
  1     42    1   100     1
  1     42    1   100     2
TPLTMI          TPLTMA          TPLTDE          TPLTDL
0.              .2504E-02       .2504E-02       .2504E-02
```

```
MOVIE   IHIST   ISPAT   IPARAM  ILINE    ISC      IDET     ISYM     IVEL   RPV      IPART
  0       0       0       0       2       0        1        0        1   .1000E+03    0
ILOW    IHIGH    JLOW   JHIGH   JPDEL   KPDEL
  1      42       1     100       2       2
ZLOW          ZHIGH          XLOW          XHIGH
-.5000E+00    .8250E+02   -.4150E+02    .4150E+02
IVX   IVZ   KLOG
 26    27     0
ISMIN ISMAX JSMIN JSMAX NCODE
  1     42    1   100     1
  1     42    1   100     2
TPLTMI          TPLTMA          TPLTDE          TPLTDL
0.              .2504E-02       .2504E-02       .2504E-02
```

Figure C.18 Three Electrode-Pair MHD Generator

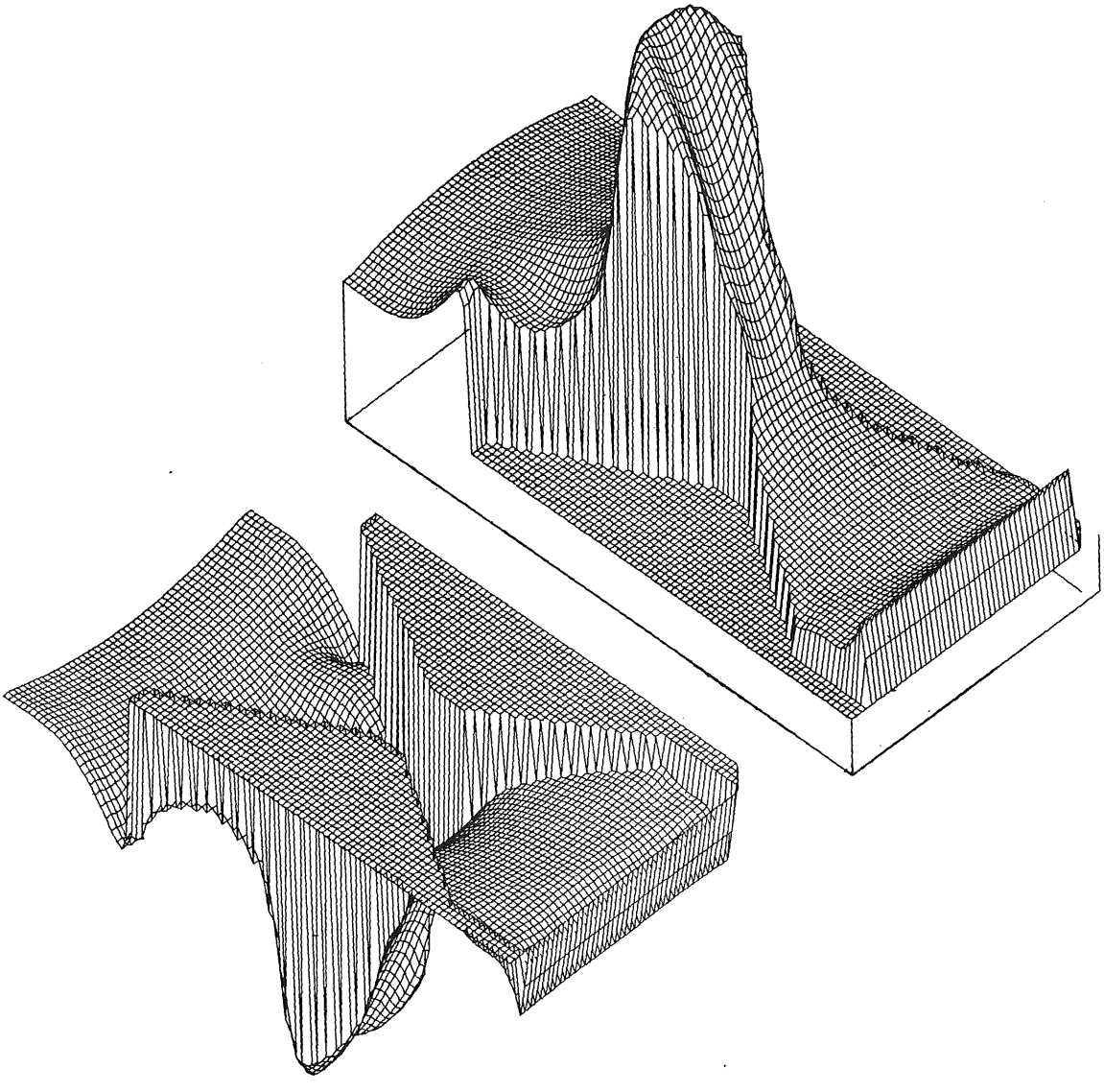


Figure C.19a Shock in a Nozzle, Two 3-D Perspectives

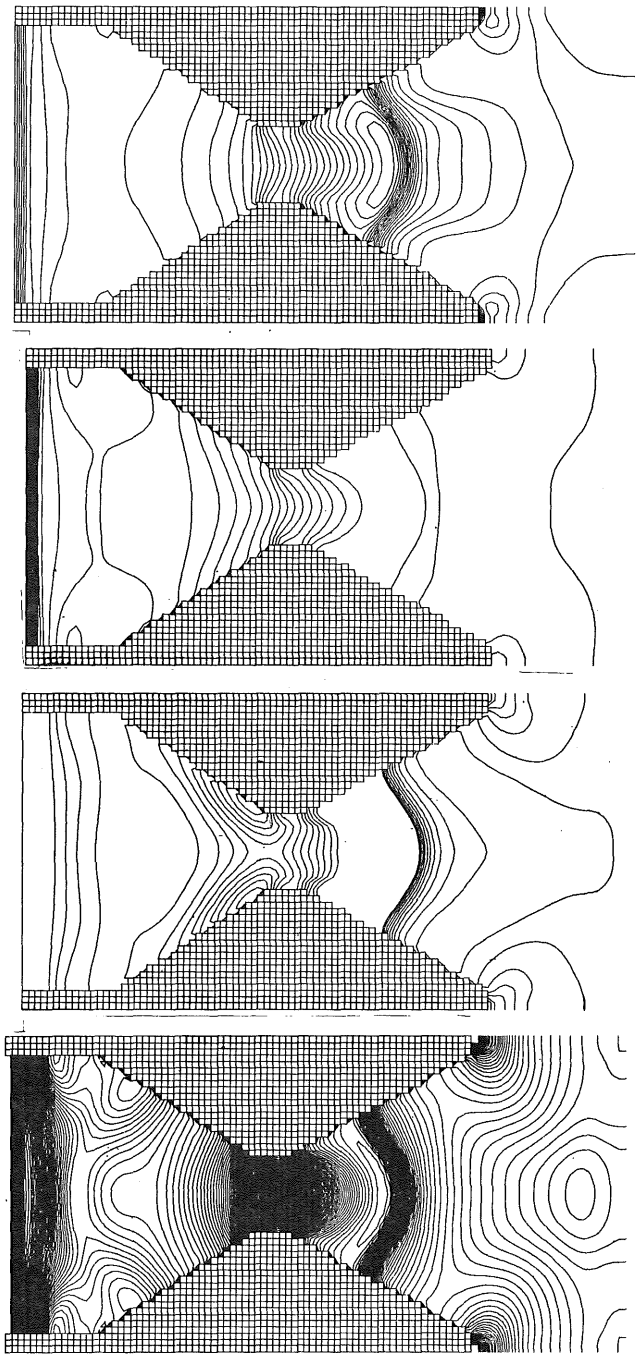


Figure C.19b Nozzle Contours. Pressure, Temperature, Density, Mach Number

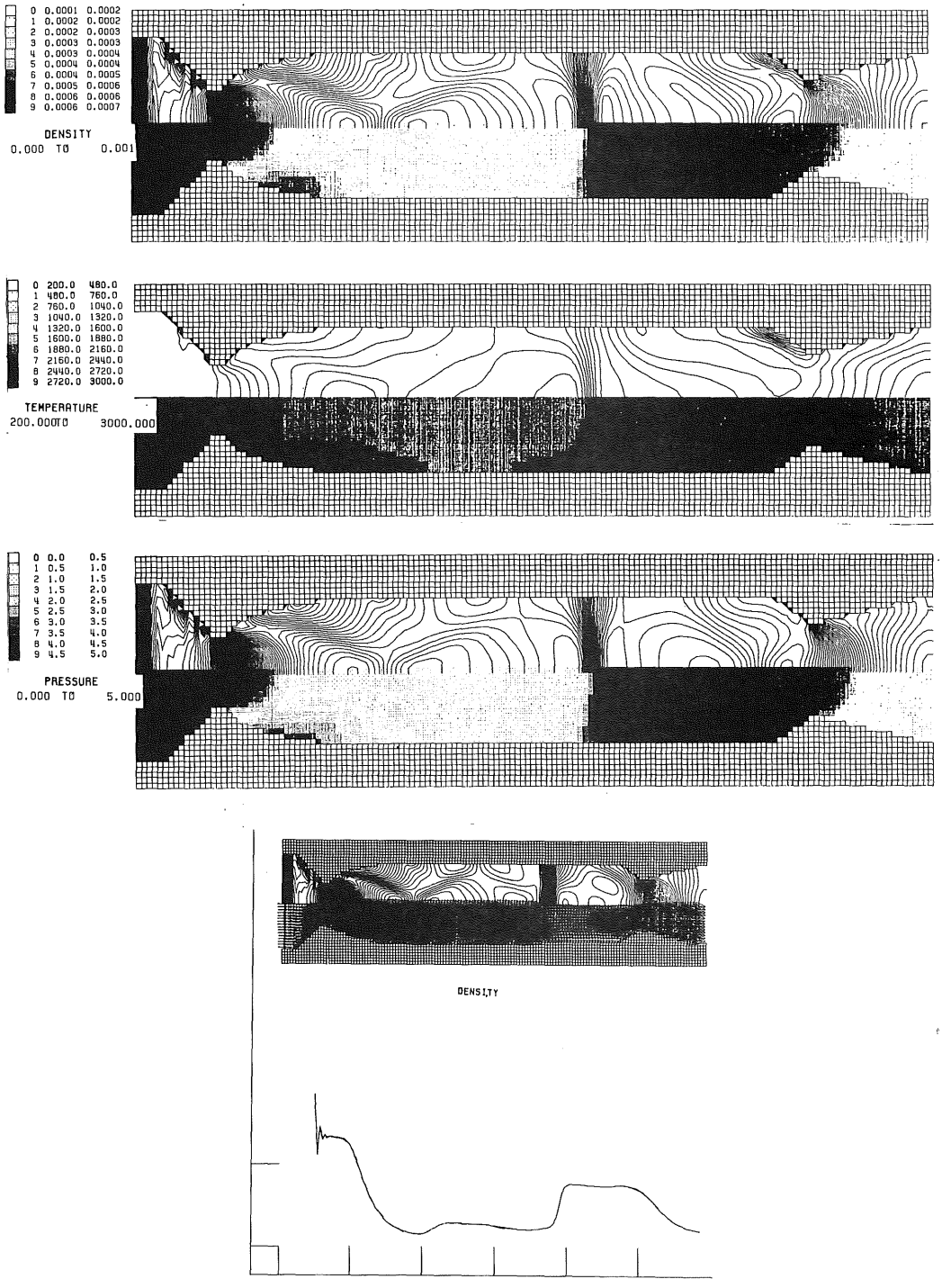
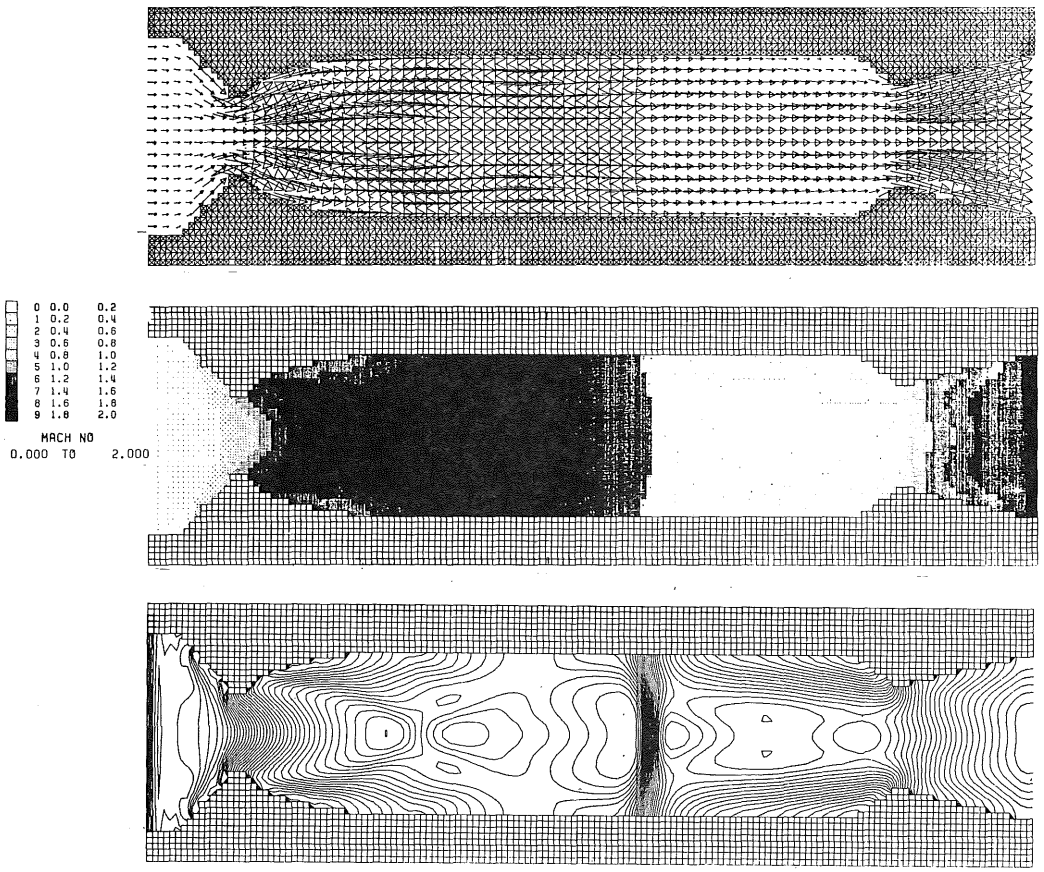


Figure C.20a Wind Tunnel Analysis



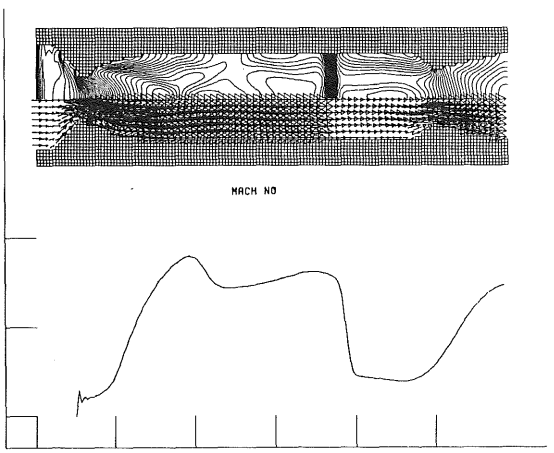


Figure C.20b Wind Tunnel Analysis

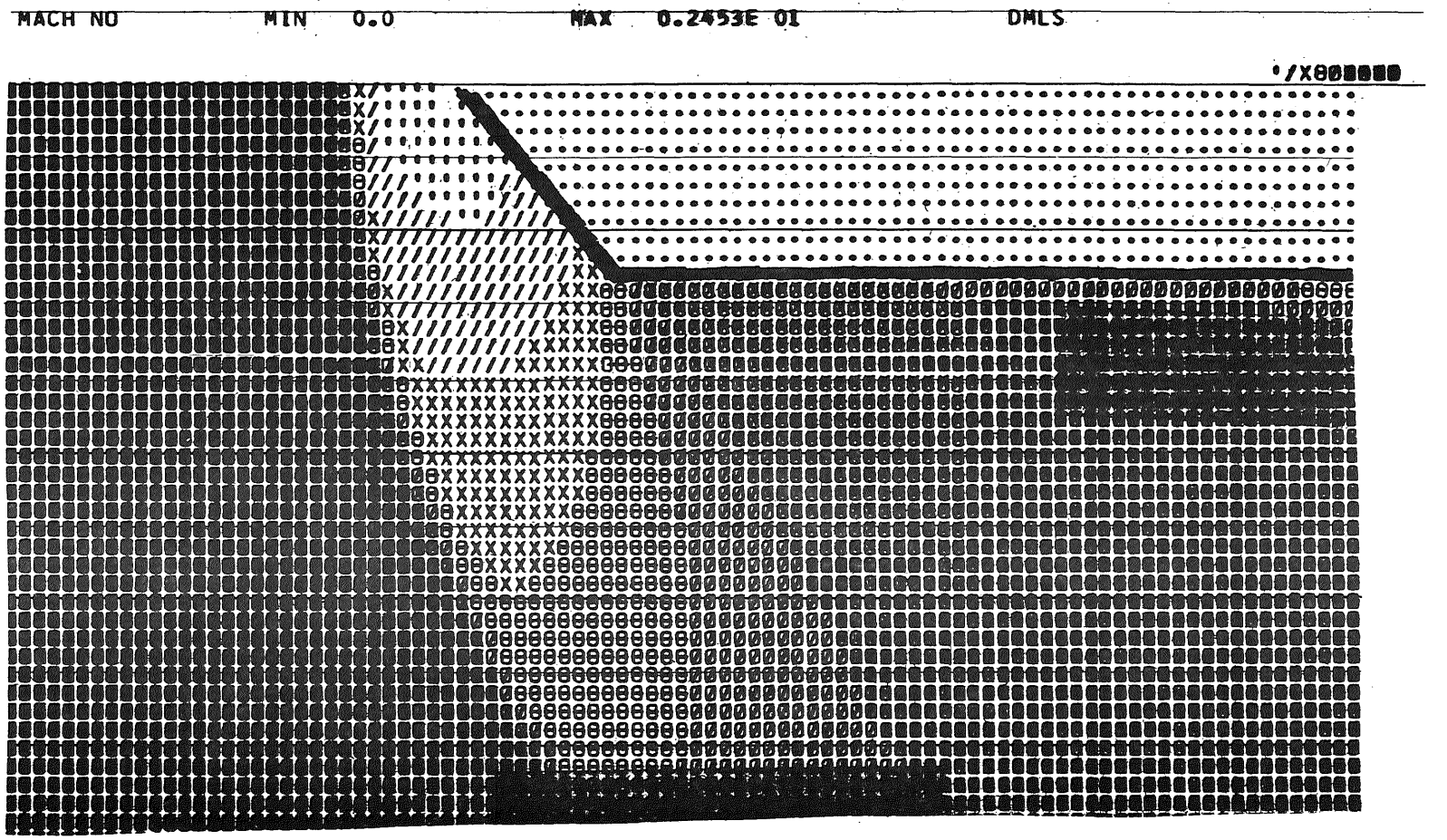


Figure C.21 Digital Plot of Flow Over Sharp-Nosed Projectile

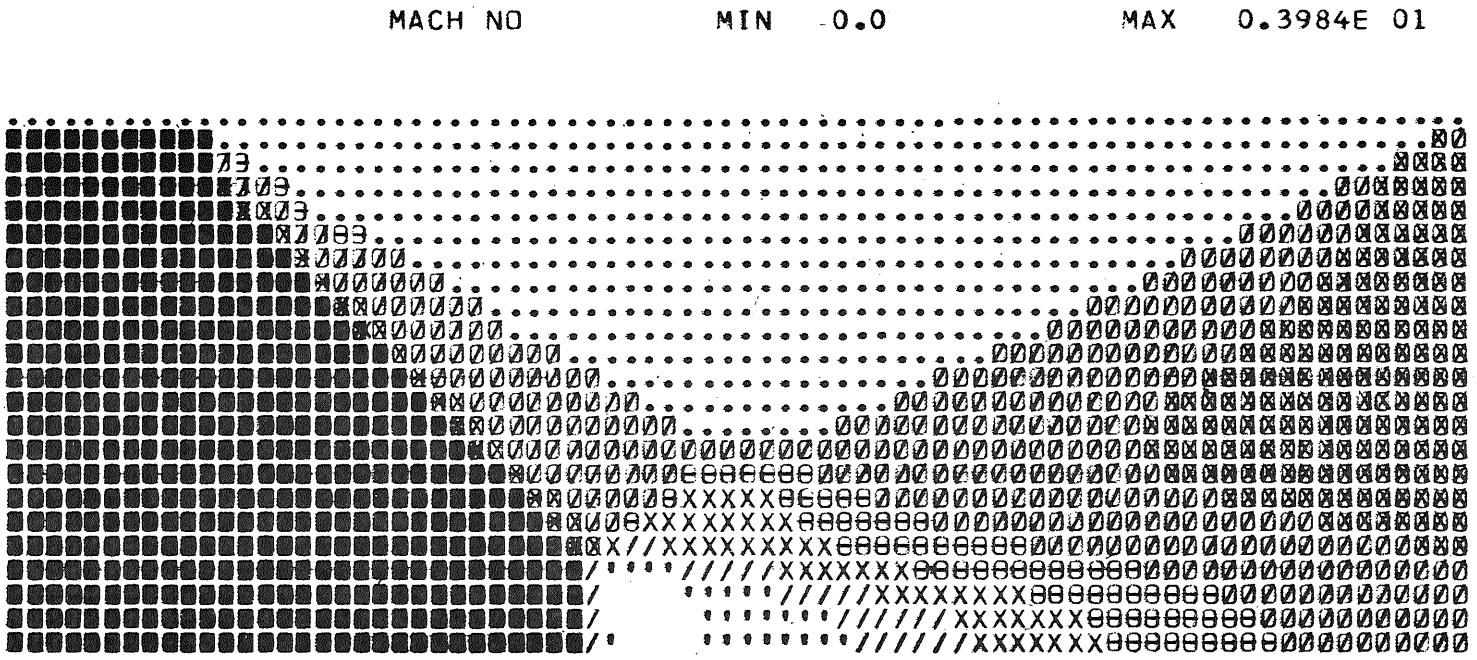


Figure C.22 Digital Plot of Mach Stem

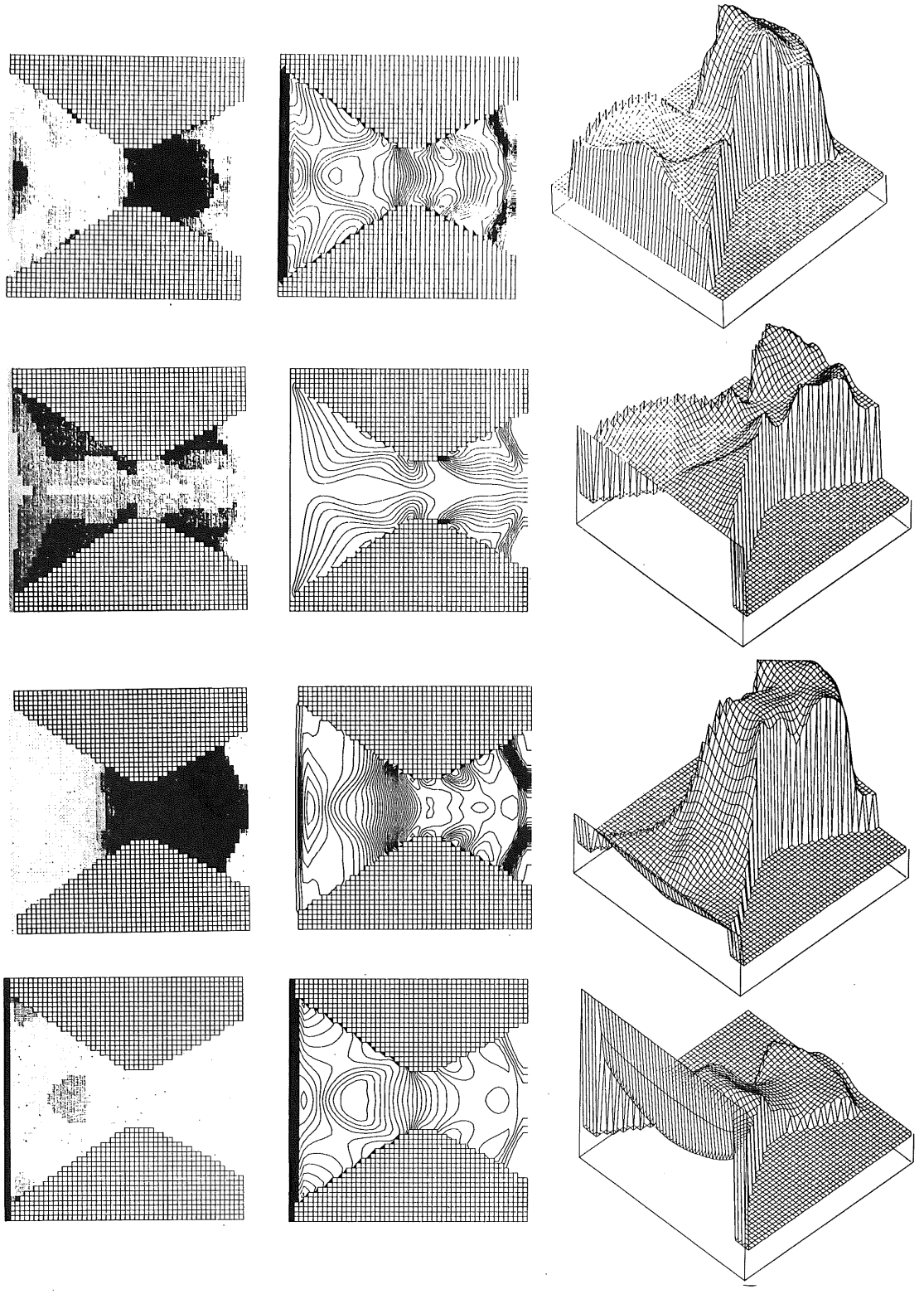
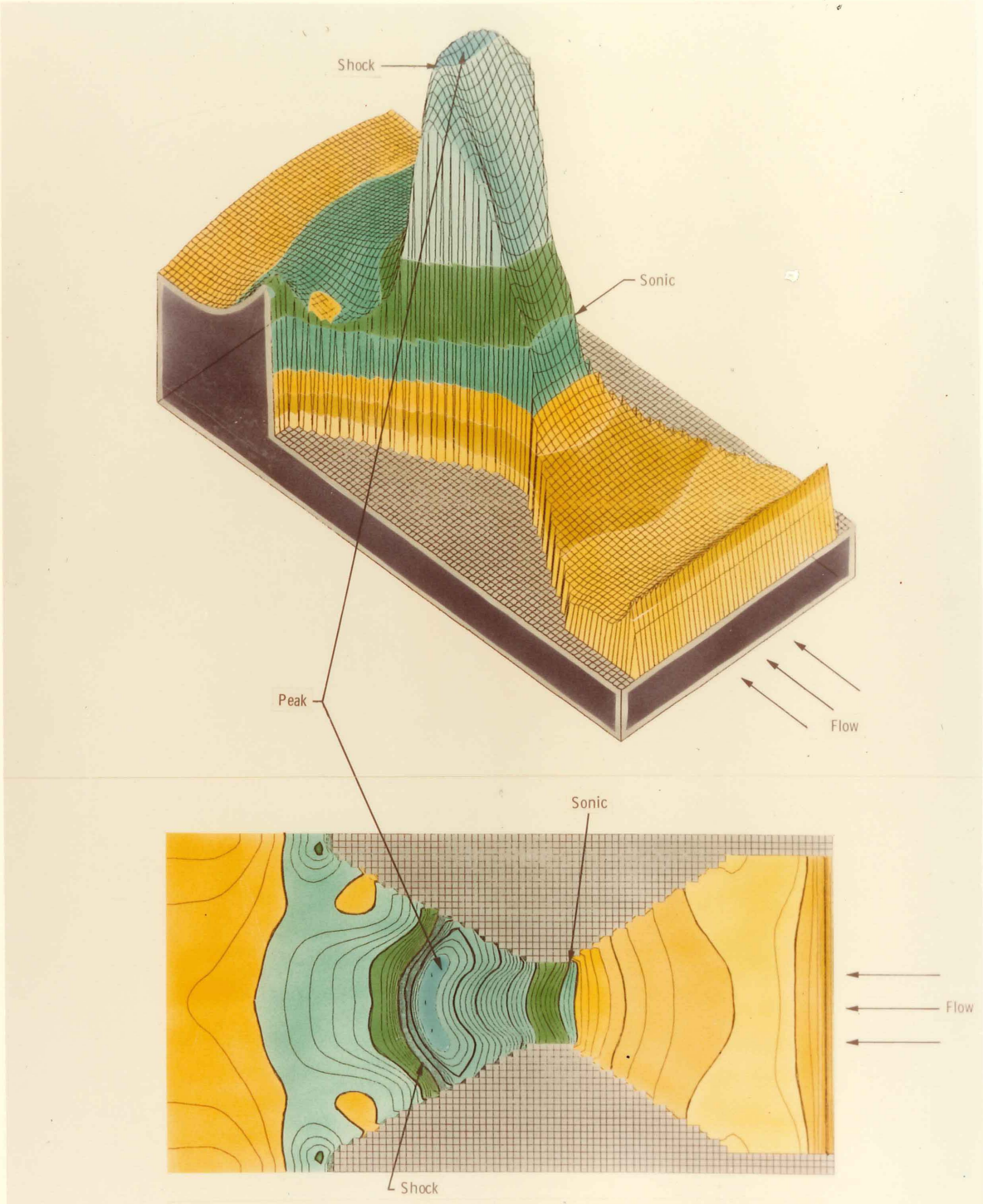


Figure C.23 Pressure, Temperature, Mach Number and Density in a Nozzle



Contour mapping alone does not provide information relating to the gradient direction. However, supplementing these maps with a 3-D perspective, the peaks and valleys become apparent. Color is used in this figure to emphasize regions of similar Mach number.

Figure C.23 Continued

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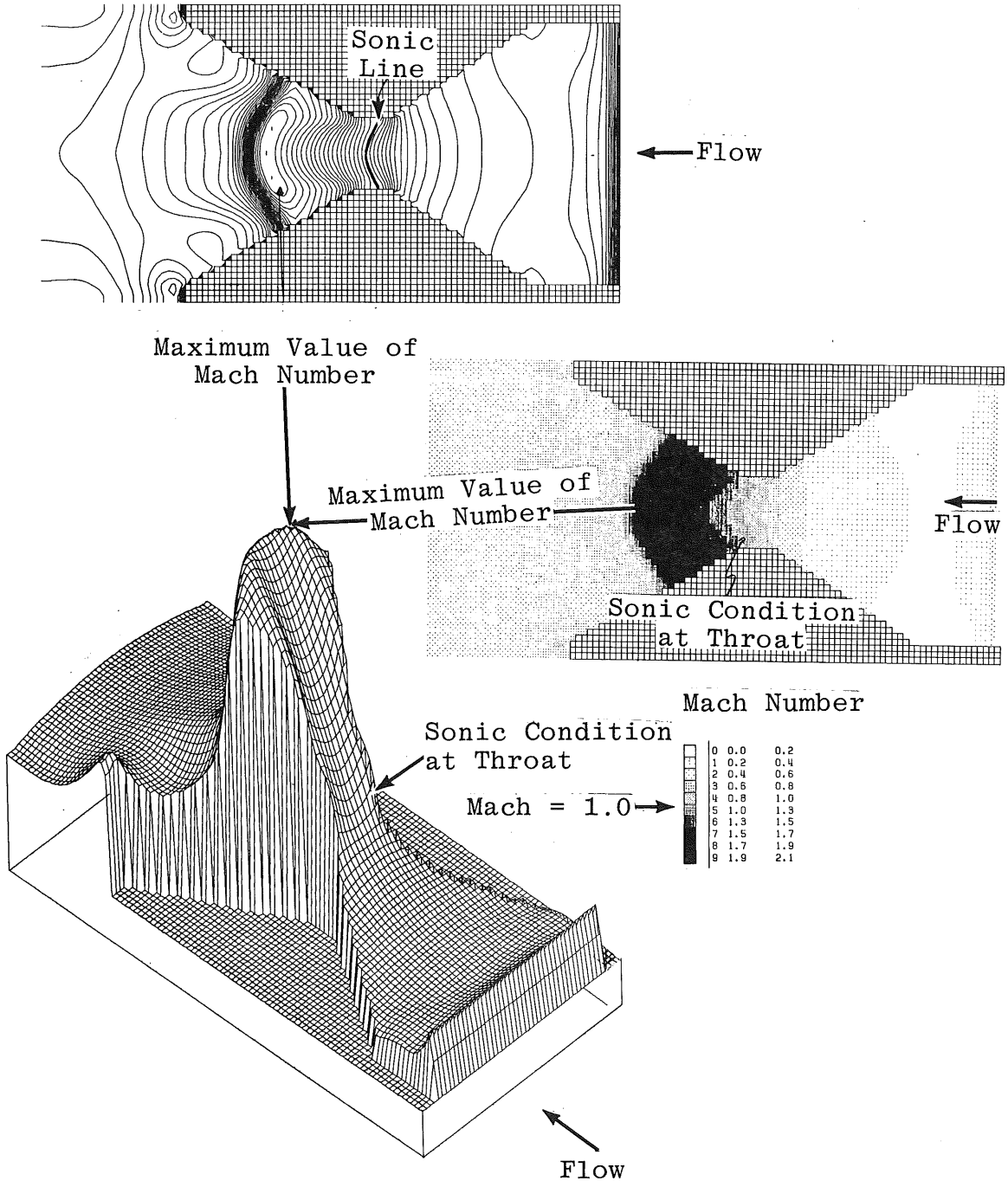


Figure C.23 Continued

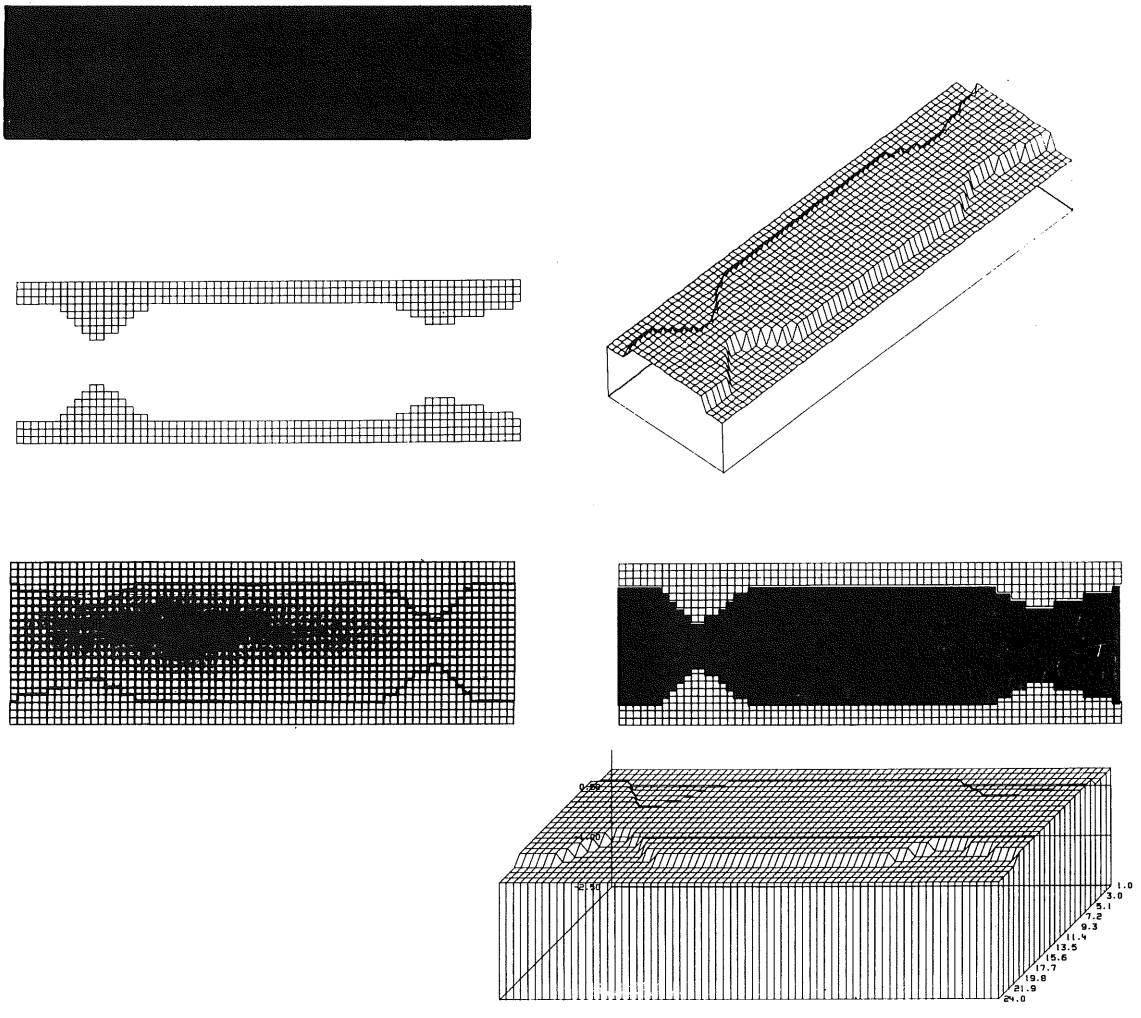


Figure C.24 MHD Generator Grid

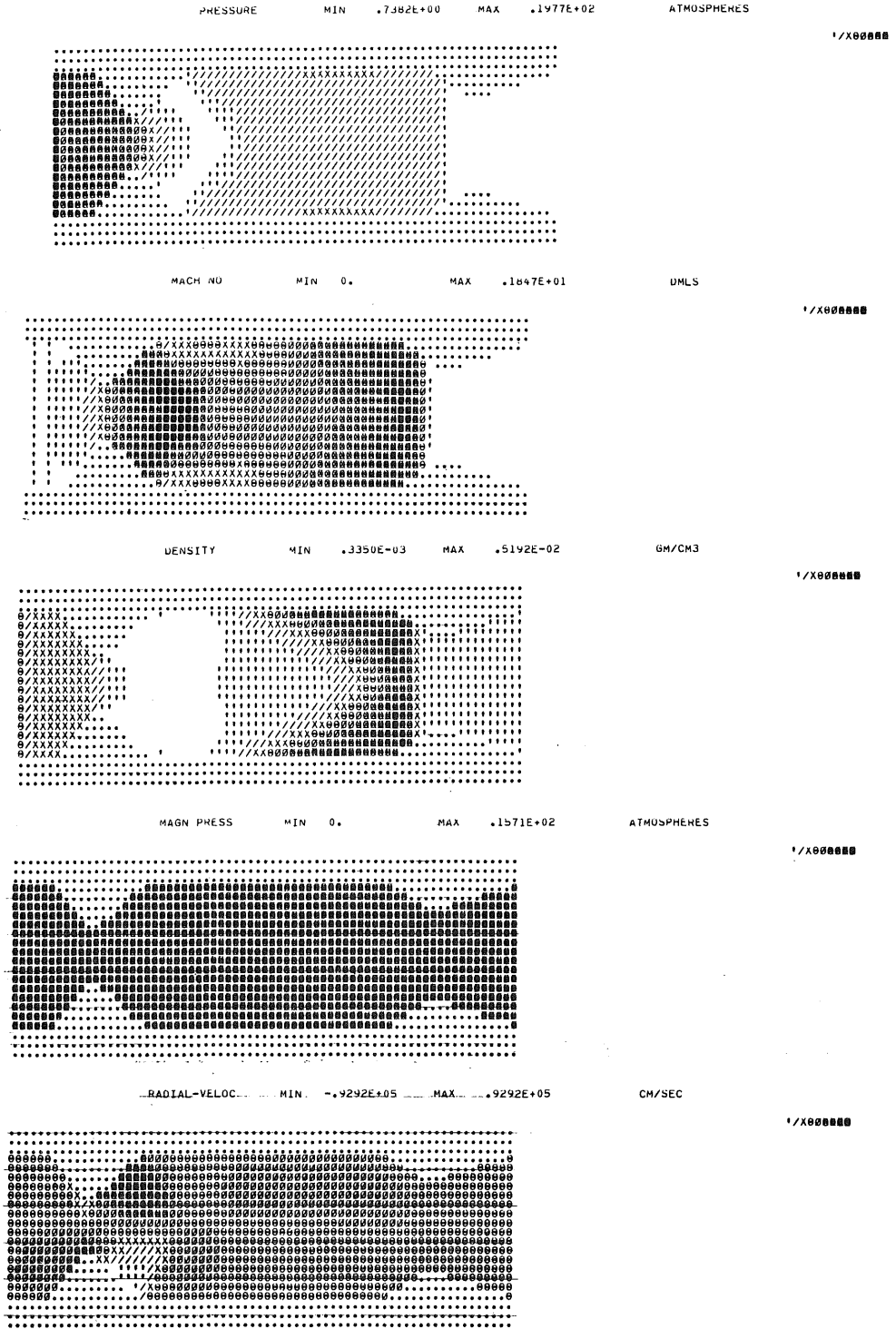


Figure C.25 Digital Plot of MHD Generator Variables

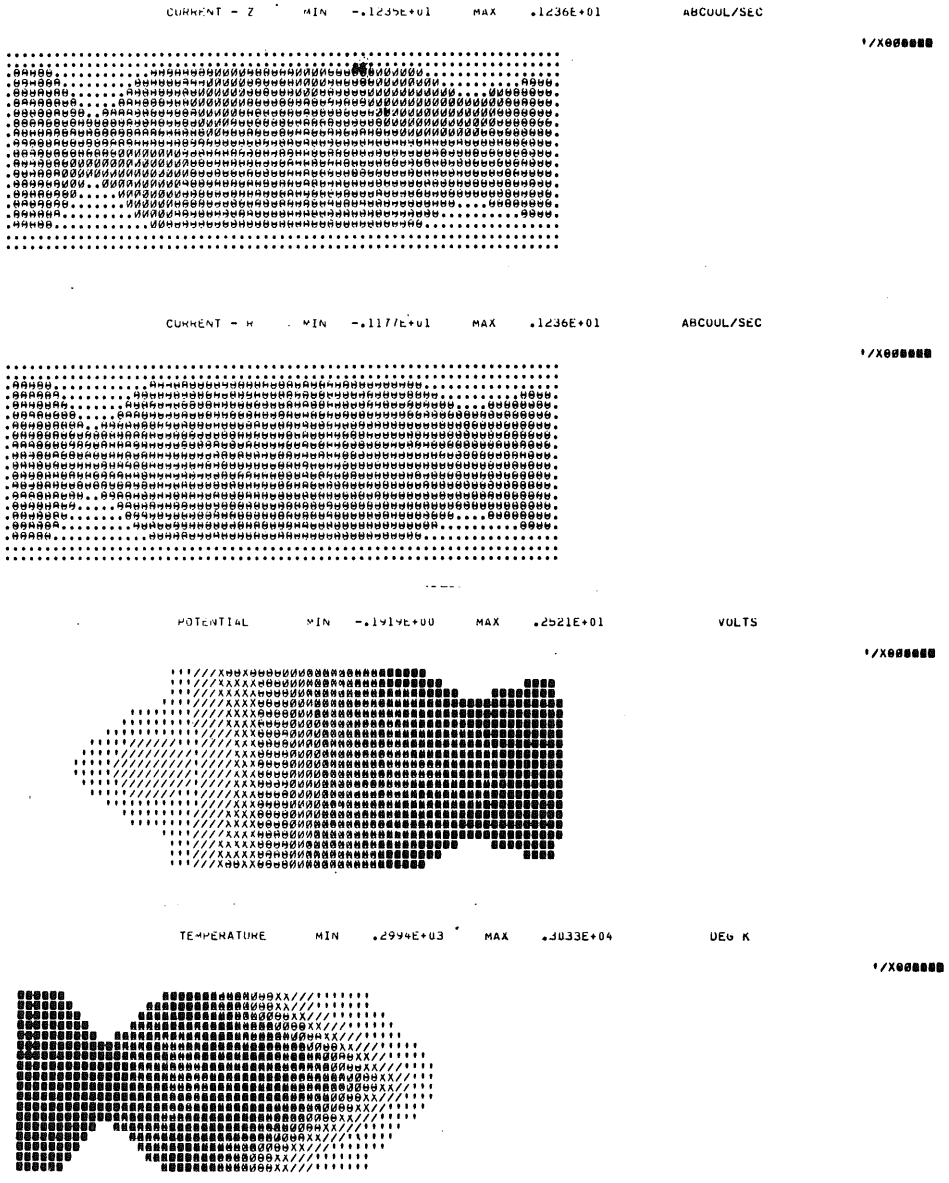


Figure C.25 Continued

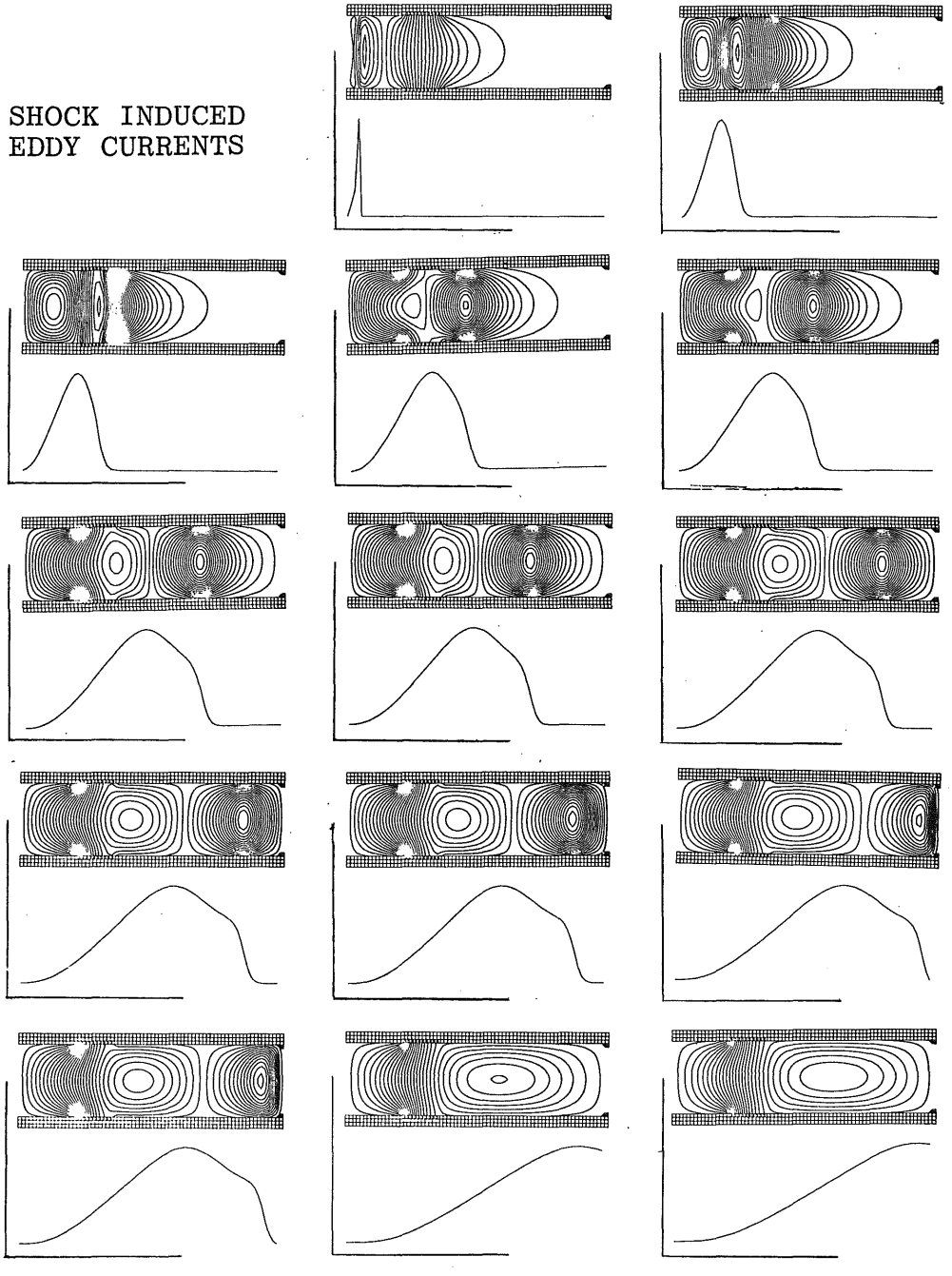


Figure C.26 Eddy Currents in an MHD Channel, Induced by a Shock (16-mm Computer Movie)

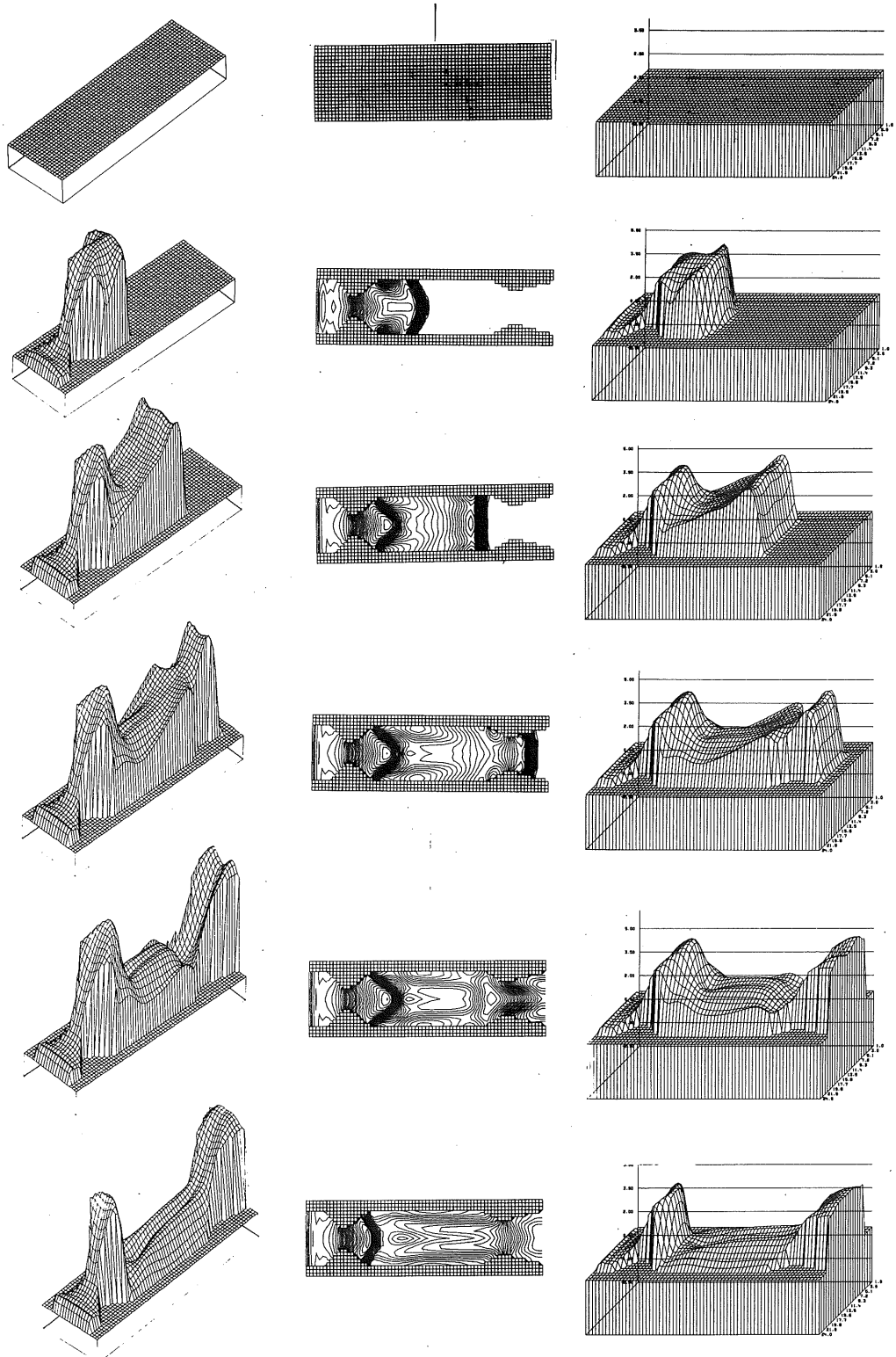


Figure C.27 Transient Pressure Distribution (16-mm Computer Movie)

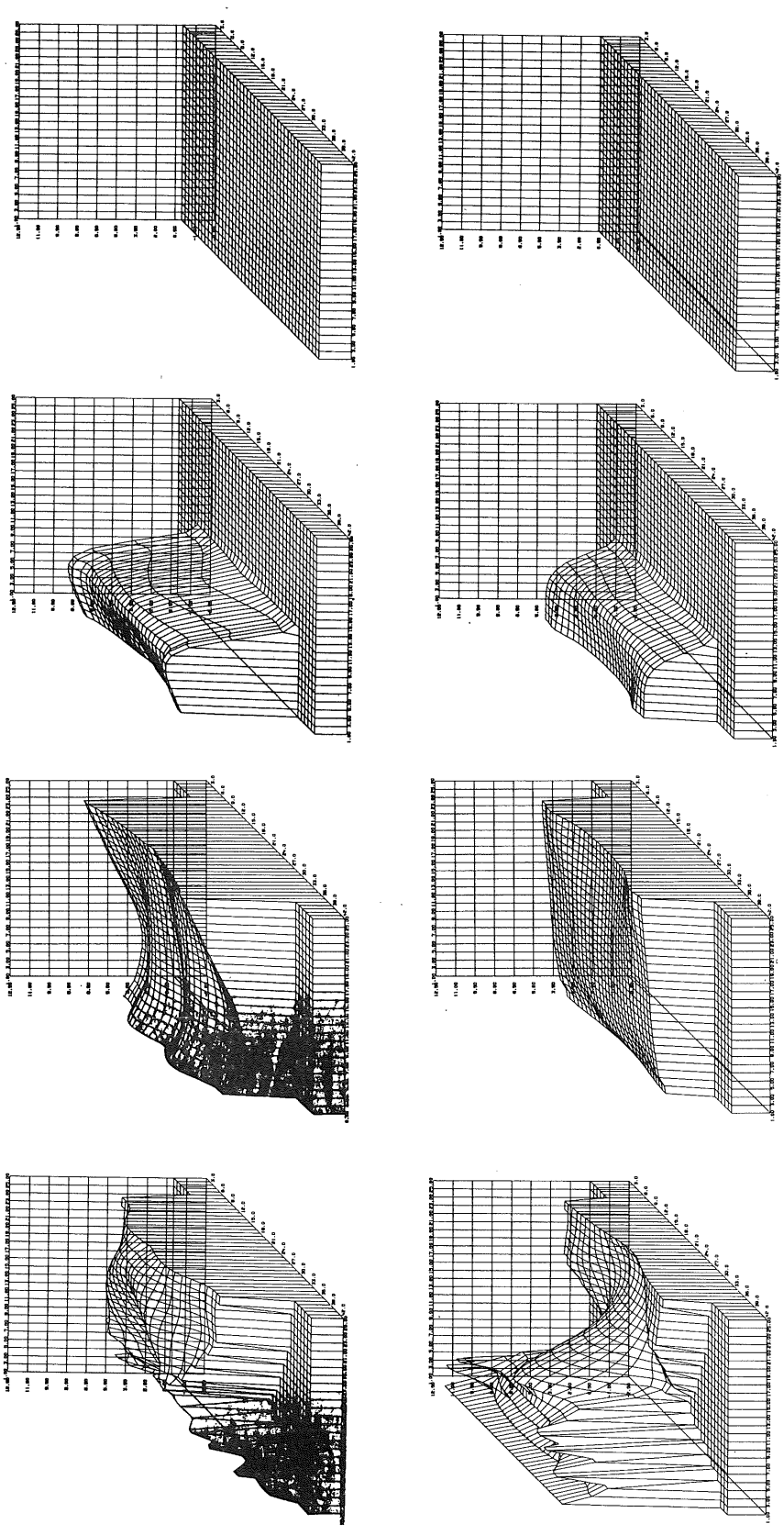


Figure C.28 Sectional View of 3-D Plot

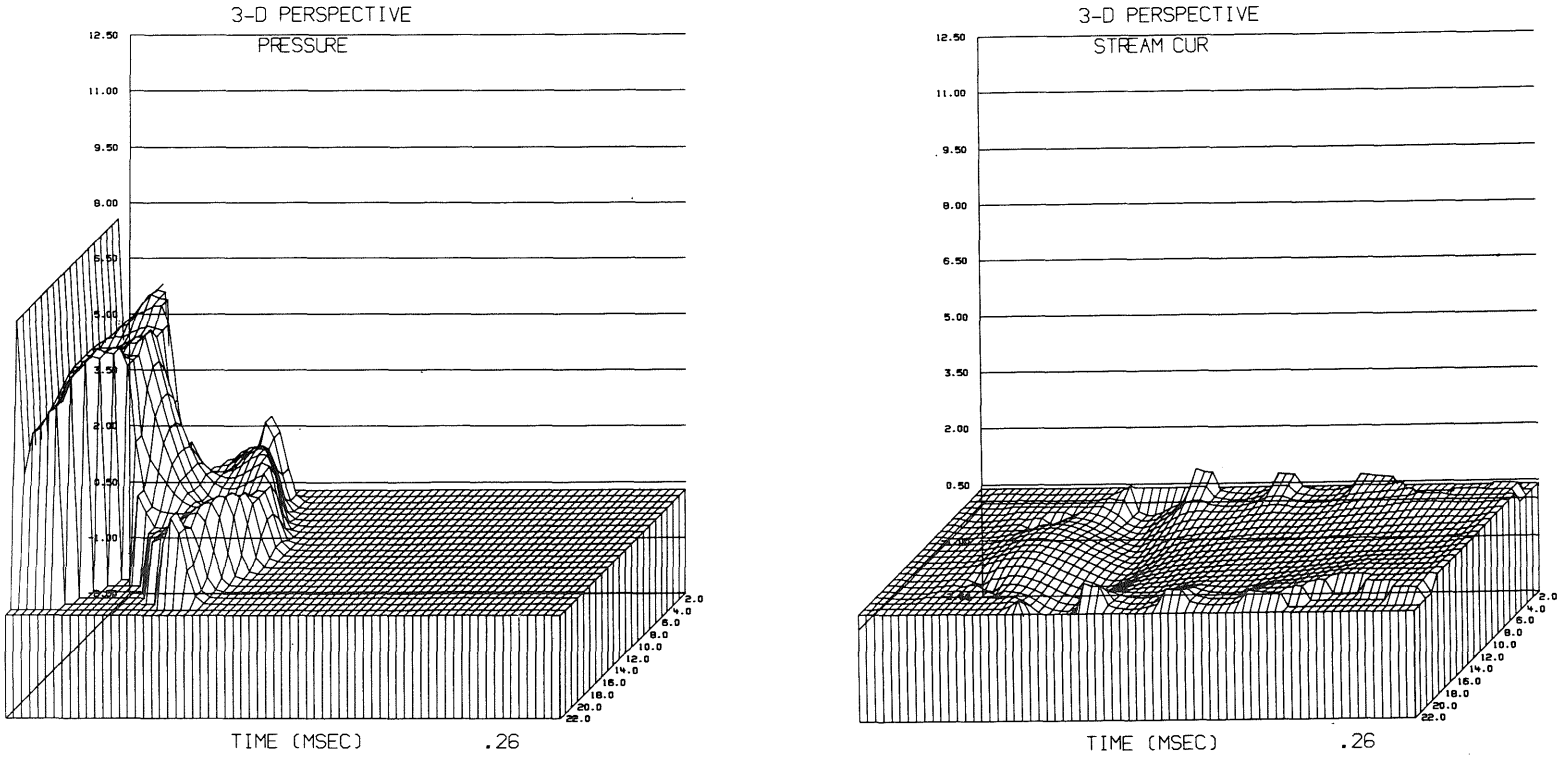


Figure C.29 Initial 3-D Distributions of Pressure and Current Stream Functions (16-mm Computer Movie)

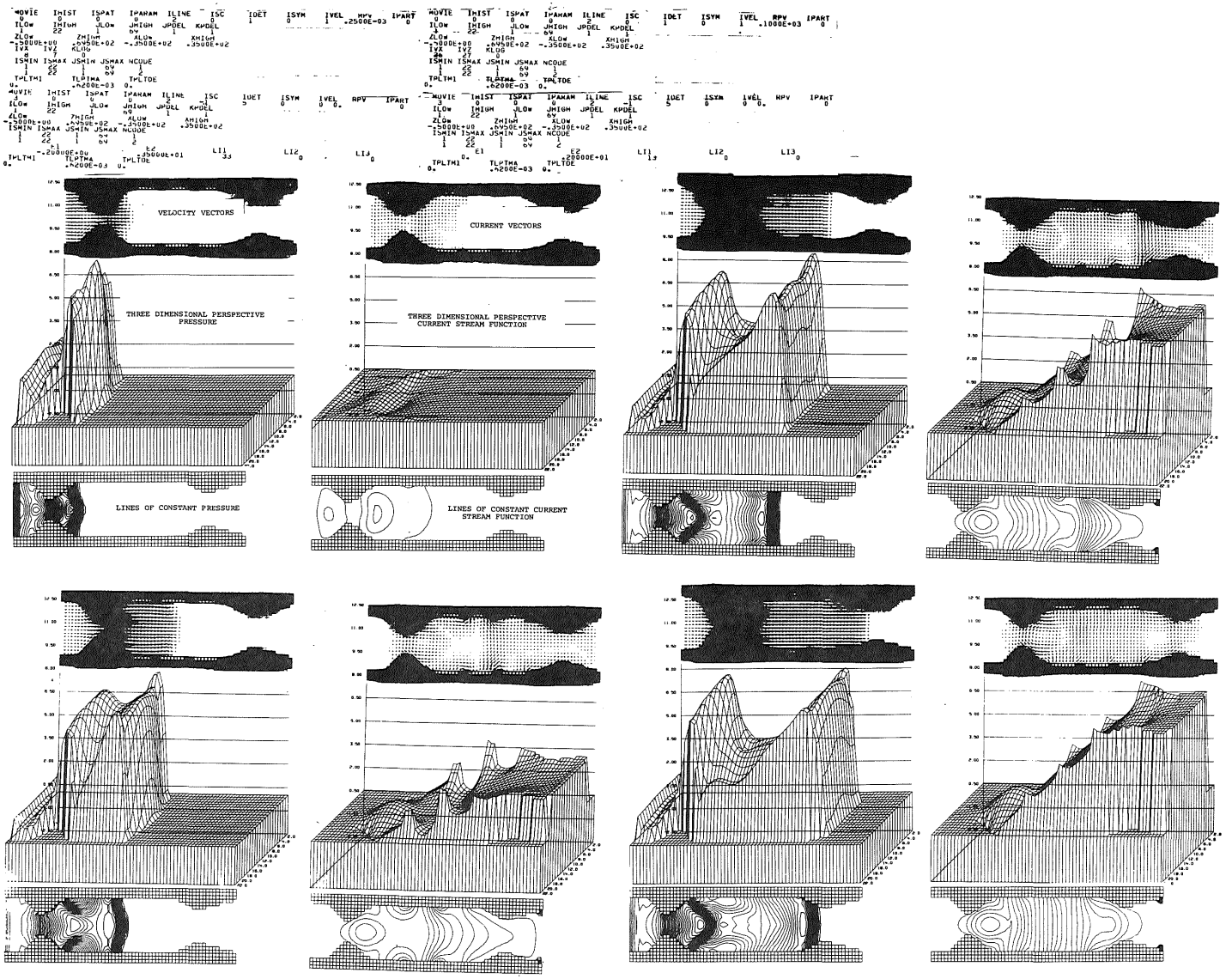


Figure C.30 Transient Calculation of P and ψ (16-mm Computer Movie)

C.5 TEST CASES

This section contains a list of card inputs for approximately 20 "test cases" which were used to develop the numerical solutions presented in this report. A list of these cases and their central processor execution times follows.

	Title	Location	Cycles	CP+ Minutes	Grid
1.	Flat Plate	Auburn	300	65	25 x 150
2.	MHD Generator-Inviscid	Auburn	200	41	20 x 150
3.	Simple Nozzle	Auburn	100	21	48 x 48
4.	SOR	Auburn	10	4	14 x 40
5.	Inviscid Nozzle Flow	Auburn	50	15	48 x 98
6.	Couette MHD	Auburn	2500	12	9 x 3
7.	Shock Tube (Theta-Field)	AEDC	200	4	10 x 97
8.	Turbulence	AEDC	200	4	25 x 50
9.	M-117	Auburn	25	87	100 x 300
10.	Nozzle Flow	Auburn	250	35	25 x 80
11.	Ablated RV*	AEDC	20000	127	50 x 100
12.	Nozzle Choking/Shocks*	AEDC	2000	109	25 x 80
13.	Shock Induced Eddies*	AEDC	200	238	24 x 70
14.	Sonic Line	AEDC	1000	71	50 x 110
15.	3 Electrodes	AEDC	100	6	30 x 103
16.	Nozzle Flow	AEDC	200	4	25 x 49
17.	One Electrode (Beta = 5)*	AEDC	75	13	24 x 40
18.	Projectile	AEDC	800	91	50 x 110
19.	Re-Entry Vehicle (M = 22)	AEDC	250	40	50 x 150
20.	Viscous Diffusion	AEDC	100	8 sec	9 x 3
21.	Couette Flow	AEDC	260	15 sec	9 x 3
22.	Thermal Couette	AEDC	1100	1	9 x 3
23.	Sound Wave	AEDC	200	5	14 x 40
24.	MHD Generator	Eglin	1000	200	42 x 98

Auburn Computer: IBM 370 (5/1)+

AEDC Computer: IBM 370 158

Eglin Computer: CDC 6600

+CP Time Based on CDC 6600

*Generated Movie → CP Time Predominately for Graphic Commands

```
 REGULAR-IRREGULAR(MACH) REFLECT
   44  150    0    0   -1    0   -1    1    1    1    0    1    4
4.5        1.9        1.8        7.1        1.8        8.5        4.5        15.
   10   15   15    2    1   10
0.1000E 000.1000E 00-.5000E-01-.5000E-010.0        0.1000E 010.7500E 00
0.00128   0.         0.         0.1956E 10
0.         1.        29.        0.
    1    1   46    1
0.0067    100000.    0.         0.6125E 10
0.         1.


    3    0    0    0    2   -1    1    0    0    0.
    1   46    1   85    1   46    1  152
2.         6.         0.         4.
    1   46    1  152    1
    1   46    1  152    2
0.        50.                   9
0.         1.         1.         1.
    3    0    0    0    2   -1    0    0    0    0.
    1   46    1  152
1.         8.5       -1.0       6.5
    1   46    1  152    1
    1   46    1  152    2
0.        50.                   9
0.         1.         1.         1.
    0    0    2    0    2
    1   46    1  152
-12.5     27.5       -30.       10.
    1   46    1  152    1
    1   46    1  152    2
    1    1    1  152    9
    1    1    1  152   13
0.         1.
    0    0    0    0    2    0    0    0    1    0.00015
    1   46    1  152                        3    2
-0.5       7.5       -1.5       6.5
    8    7
    1   46    1  152    1
    1   46    1  152    2
0.         1.         1.         1.
    0    0    0    0    2   -1    0    0    0    0.
    1   46    1  152
1.0        8.5       -1.0       6.5
    1   46    1  152    1
    1   46    1  152    2
0.95      16.5                   9
0.         1.         1.         1.
    0    0    0    0    2   -1    0    0    0    0.
    1   46    1  152
1.0        8.5       -1.0       6.5
    1   46    1  152    1
    1   46    1  152    2
0.1        3.9                  13
0.         1.         1.         1.
    0    0    0    0    2         1                              1
    1   46    1  152
0.5        8.5       -2.5       5.5
    2   20   10   10    3
    1   46    1  152    1
    1   46    1  152    2
0.         1.         1.         1.
```

```
    M-117 SUBSONIC
  100  300    1   50    1    0   -1    1    1    1    0    1   15    0
0.        0.        -0.12      0.1       -0.21      0.2       -0.28      0.3
-0.34     0.4       -0.39      0.5       -0.43      0.6       -0.46      0.7
-0.48     0.8       -0.49      0.9       -0.495     1.        -0.498     1.1
-0.5      1.2       -0.5       2.4       0.         6.
    1   15   15    1    0   -1
0.06      0.0333333 -6.060     -3.37995  0.         1.        0.75
0.001314  0.        0.         0.2406E 10
1.        1.        29.        0.
    1    1  102  302
0.001314  15000.    0.         0.1956E 10
1.        1.


    0    0    0    0    2   -1    0    2    0      0.0010
    1  102   75  225    1  102    1  302
-10.       -2.       -4.        4.
    1  102    1  302    1
    1  102    1  302    2
0.89      0.97                  9                    1
0.        1.        1.         1.
    0    0    0    0    2    0    0    2    1      0.0010
    1  102    1  302                        3    3
-10.       -2.       -4.        4.
    8    7
    1  102    1  302    1
    1  102    1  302    2
0.        1.        1.         1.
    3    0    0    0    2   -1    0    2    0      0.0010
    1  102    1  302
-10.       2.        -6.        6.
    1  102    1  302    1
    1  102    1  302    2
0.91      0.95                  9
0.        1.        1.         1.
    3    0    0    0    2   -1    0    2    0      0.0010
    1  102    1  302
-10.       -4.       -3.        3.
    1  102    1  302    1
    1  102    1  302    2
-0.75     0.25                  17
0.        1.        1.         1.
    3    0    0    0    2   -1    0    2    0      0.0010
    1  102    1  302
-10.       -4.       -3.        3.
    1  102    1  302    1
    1  102    1  302    2
0.42      0.47                  13                   1
0.        1.        1.         1.
```

```
 THERMAL DIFFUSION
   9    3                0    1    0    1                1
  10    1    2  500      1  100
1.0       .2        0.          -1.1       .01        .01        .75
1.                                100.
0.         1.         29.        0.
   1    1    1    5
1.                                200.
0.         1.

  11    1   11    5
1.                                200.
0.         1.
```

```
      FUNCTION COND(K,J,IHALF,JHALF)
      COMMON /V14/ NMAGN,NTHRM,NVISC,NCONV,IPOT
      NTHRM=1
      COND=1.
      RETURN
      END
      FUNCTION CV(K,J,KHALF,JHALF)
      CV=1.
      RETURN
      END
      SUBROUTINE HULLP1
      RETURN
      END                          Subroutines
      SUBROUTINE HULLP2            "Dummied" Out
      RETURN
      END
```

```
 MAGNETIC DIFFUSION
   9    3                0    1    0    1                1
  10    1    2  500      1  100
1.0       .2        0.          -1.1       .01        .01        .75
1.         0.         0.         1.                    100.
0.         .0796      29.        0.
   1    1    1    5
1.                                1.                  200.
0.         .0796
  11    1   11    5
1.                                1.                  200.
0.         .0796
```

```
      SUBROUTINE HULLP1
      RETURN
      END                          Subroutines
      SUBROUTINE HULLP2            "Dummied" Out
      RETURN
      END
      FUNCTION SIG(K,J,KHALF,JHALF,KJ)
      COMMON /V14/ NMAGN,NTHRM,NVISC,NCONV,IPOT
      SIG=1.
      NMAGN=1
      RETURN
      END
```

NOTE: Labelled Common Blocks V1 to V32 have since been renamed: CARRAY, COUTP, CMESH, CBOUND, etc.

```
 VISCOUS DIFFUSION
    9    3                0    1    0    1              1         -2
1.7       0.          1.7        10.
   10    1    2   50          100
1.0        .2          0.          -1.1       .01         .01         .75
1.         100.        0.          0.1929E 10
1.         1.          29.         0.
    1    1    1    5
1.         200.        0.          0.1929E 10
1.         1.
   11    1   11    5
1.         200.        0.          0.1929E 10
1.         1.

FUNCTION GAMM(I,J)
GAMM=1.
RETURN
END
```

```
                    SOUND WAVE
   14   40    0    0   -1    0   -1   -1    1    1    1    0    0
   40   10    2   10    1  100
1.         1.          -0.5        -0.5        0.          1.          0.75        0.
0.001      0.          0.          0.1956E 10
0.         1.          29.         0.
    1    1   16    1
0.0011     0.          0.          0.1956E 10
0.         1.
```

```
    0    0    1    0    2
    1   16    1   42
-1.         7.          -2.5        5.5
    1   16    1   42    1
    1   16    1   42    2
    1    1    1   42    9
0.000001  1.
    0    0    1    0    2
    1   16    1   42
-1.         7.          -2.5        5.5
    1   16    1   42    1
    1   16    1   42    2
    1    1    1   42    9
0.          0.00000001
    0    0    1    0    2
    1   16    1   42
-1.         7.          -2.5        5.5
    1   16    1   42    1
    1   16    1   42    2
    1    1    1   42    9    1
0.          1.0
```

```
  BLASIUS FLAT PLATE (RE=2500)
   25  150              1    0    1    1    1    0    1        -2
0.048     0.         0.048     0.4
   50    1    8   50    1  250
0.002     0.002     -0.001    -0.001    0.000001  0.000001  1.
0.001                          .1929 E 10
0.0001    1.         29.       0.
    1    1   27  152
0.001     833.33               .19290E 10
0.0001    1.

    0    0    0    0    2    0    1    0    1     125.
    1   22    1   42                        10    1
-1.       5.        -1.       5.
    8    7
    1   22    1   42    1
    1   22    1   42    2
0.        1.        1.        1.

       TURBULENT JET
   25   50              0    1    0    1    0    1    2
  100    1   10  200    1  200
0.01      0.005     -0.005    -0.0650   .00001    .00001    1.
0.0023                         1.0
0.0023    1.         29.
   14    1   27   52
0.0023    1.0                  1.5
0.0023    1.

    3    0    0    0    2   -1    0    0
    1   27    1   52
-0.05     0.20      -0.125    0.125
    1   27    1   52    1
    1   27    1   52    2
-0.1      1.1                 7
0.        1.        1.        1.
    0    0    0    0    2    0    1    0    1     125.
    1   27    1   52                        5    1
-0.05     0.20      -0.125    0.125
    8    7
    1   27    1   52    1
    1   27    1   52    2
0.        1.        1.        1.
    0    0    0    0    2   -1    0    0
    1   27    1   52
-0.15     0.10      -0.125    0.125
    1   27    1   52    1
    1   27    1   52    2
0.01      0.99                7
0.        1.        1.        1.
      FUNCTION EDDY (I,J )
      COMMON /V1/ R(52),Z(152),DR(52),DZ(152),U(52,152),V(52,152),
     1E(52,152),RHO(52,152),B(52,152)
      REAL R*8
      U1=1.0
      EDDY=0.014*0.098*Z(J)*U1
      RETURN
      END

      FUNCTION GAMM(I,J)
      GAMM=1.0
      RETURN
      END
```

```
  COUETTE FLOW
    9    3                    1          1    1    0    1
   100    1    1  100       1000
1.          .2                            .0100      .0125      1.
0.0023                              .1929 E 10
0.0023      1.         29.          0.
    1     1    1    5
0.0023                              .1929 E 10
0.0023      1.
   11     1   11    5
0.0023      1.                      .1929 E 10
0.0023      1.


      FUNCTION GAMM(I,J)
      GAMM=1.1
      RETURN
      END
      SUBROUTINE SPEC
      COMMON /V1/ R(16),Z(042),DR(16),DZ(042),U(16,042),V(16,042),
     1E(16,042),RHO(16,042),B(16,042)
      COMMON /V4/ KMAX,JMAX,KP1,JP1,KP2,JP2,IAXI,ITURB,ISYM(4)
      EO=1000.
      P=-5.*P
      DO 1 J=1,JP2
      DO 1 K=1,KP2
      CJ=J
      RHO(K,J)=0.0023
      V(K,J)=0.
      E(K,J)=CJ*P+EO
    1 CONTINUE
      RETURN
      END
   COUETTE FLOW WITH HEAT TRANSFER
    9    3                    1          1    1    0    1
 1000    1    1  100       1000
1.          0.1                        -0.05      .0050      .0050      1.
0.0023                              1.0
0.0023      1.         29.          0.
    1     1    1    5
0.0023                              1.
0.0023      1.
   11     1   11    5
0.0023      1.                      1.5
0.0023      1.


               1          2
    1    12    1    5
-110.       290.        -350.       50.
    1    12    1    5    1
    1    12    1    5    2
    1    12    4    4    7
0.          1.          1.          1.


      FUNCTION GAMM(I,J)
      COMMON /V2/ VISC
      DATA IKT/0/
      GAMM=1.0
```

```
      RETURN
      END
      SUBROUTINE SPEC
      COMMON /V1/ R(16),Z(042),DR(16),DZ(042),U(16,042),V(16,042),
     1E(16,042),RHO(16,042),B(16,042)
      COMMON /V4/ KMAX,JMAX,KP1,JP1,KP2,JP2,IAXI,ITURB,ISYM(4)
      DO 1 J=1,JP2
      DO 1 K=1,KP2
      CJ=J
      RHO(K,J)=0.0023
      V(K,J)=0.
    1 CONTINUE
      RETURN
      END
      FUNCTION COND(K,J,IHALF,JHALF)
      COMMON /V14/ NMAGN,NTHRM,NVISC,NCONV,IPOT
      NTHRM=1
      COND=1./8.*0.0023
      RETURN
      END
      FUNCTION CV(K,J,KHALF,JHALF)
      CV=1.
      RETURN
      END
```

```
COUETTE MHD
    9    3                    1         1    1    0    4
  250    1    1  500      2500
1.         .2                              .0005     .0005     0.05
1.0                        .1929 E 10          2.
1.0         1.        29.        0.
    1    1    1    5
1.0         1.                  .1929 E 10          2.
1.0         1.
   11    1   11    5
1.0         0.                  .1929 E 10          2.
1.0         1.
                1         2
    1   12    1    5
-110.      290.       -350.      50.
    1   12    1    5    1
    1   12    1    5    2
    1   12    4    4    7
0.          1.         1.         1.
      SUBROUTINE SPEC
      COMMON /V1/ R(52),Z(152),DR(52),DZ(152),U(52,152),V(52,152),
     1E(52,152),RHO(52,152),B(52,152)
      COMMON /V4/ KMAX,JMAX,KP1,JP1,KP2,JP2,IAXI,ITURB,ISYM(4)
      COMMON /V6/ TIME,DT,NCYCLE,NMAX,MINDT,MAXDT
      COMMON /V23/ BR(52,177),BZ(52,177)
      REAL R*8
      DO 1 J=1,JP2
      BZ(11,J)=0.
      BZ(1,J)=BZ(2,J)
    1 CONTINUE
      RETURN
      END
      FUNCTION SIG(I,J,K,L,M)
      COMMON /V14/ NMAGN,NTHRM,NVISC,NCONV,IPOT
      SIG=1.0
      NMAGN=1
      RETURN
      END
      FUNCTION GAMM(I,J)
      GAMM=1.0
      RETURN
      END
```

```
  SHOCK TUBE (NO FIELDS)
    3   97    0    0   -1    1   -1    1    1    1    0    0    2
4.        0.        4.        100.
  200    2    3  200    1  200
1.0       0.1       0.        0.        .00000001 .1        .75       0.
0.01314                       0.1957E 10
0.        1.        29.       0.
    1    1    5   48
0.01314                       0.1957E 10
0.        1.
    1   49    5   99
0.001314                      0.1957E 10
0.        1.



    0    0    6    0    2              2    0     .001
    1    5    1   99                        3    2
-1.       99.       -70.      30.
    1    5    1   99    1

    1    5    1   99    2
    2    2    1   99    7
    2    2    1   99    9
    2    2    1   99   11
    2    2    1   99   13
    2    2    1   99   14
    2    2    1   99   16
0.        1.        0.        0.
   SHOCK TUBE ( THETA FIELD )
    3   97    0    0   -1    1   -1    1    1    1    3    0    0
  200    2    3  200    1  200
1.0       0.1       0.        0.        .00000001 .1        .35       0.
0.01314                       0.1957E 1010000.
0.        1.        29.       0.
    1    1    5   48
0.01314                       0.1957E 1010000.
0.        1.
    1   49    5   99
0.001314                      0.1957E 1010000.
0.        1.

    0    0    0    0    2   -1    2    0    0     .001
    1   12    1   99                        3    2
-1.       99.       -70.      30.
    1   12    1   99    1
    1   12    1   99    2
6500.     12500.            16
0.        1.        1.        1.
    0    0    6    0    2              2    0     .001
    1    5    1   99                        3    2
-1.       99.       -70.      30.
    1    5    1   99    1
    1    5    1   99    2
    2    2    1   99    7
    2    2    1   99    9
    2    2    1   99   11
    2    2    1   99   13
    2    2    1   99   14
    2    2    1   99   16
0.        1.        1.        1.
```

```
  ABLATED RE-ENTRY VEHICLE
   50  100              0   -1    1    1    1    1    0    1   16
-38.       0.        -38.0      1.       -37.      1.5      -28.      5.
-26.       6.        -24.       7.5      -23.      8.3      -22.      9.5
-21.       11.       -20.       12.8     -19.      15.      -18.      17.4
-17.       19.       -16.       20.      -15.      20.6     0.        22.0
  500    5    5   50    1 1500
1.00       1.00      -0.5       -51.50    0.       1.       0.75
0.00134                         .1929 E 10
0.         1.        29.        0.
    1    1    1  102
0.00268    0.000     300000.    4.6929E 10
0.         1.



    3    0    0    0    2   -1    0    1    1     .00015
    1   52    1  102
-60.      10.       -50.       0.
    8    7
    1   52    1  102    1
    1   52    1  102    2

0.         200.               9                   1
0.         1.
    3    0    0    0    2   -1    0    1    0     .00015
    1   52    1  102
-60.      10.       -50.       0.
    1   52    1  102    1
    1   52    1  102    2
0.         9.                 13.
0.         1.        1.       1.
    0    0    0    0    2   -1    0    1    0     .00015
    1   52    1  102
-60.      10.       -50.       0.
    1   52    1  102    1
    1   52    1  102    2
0.         4100.              31
0.         1.
    3    0    0    0    2   -1    0    1    0     .00015
    1   52    1  102
-60.      10.       -50.       0.
    1   52    1  102    1
    1   52    1  102    2
0.         4100.              31                  1
0.         1.        0.       0.



   RE-ENTRY VEHICLE M=22
   50  150    0    0    1    0   -1    1    1    1    1    1   -4
0.         37.       -2.        39.       -6.       43.       -16.      92.
  250   10   10   50    1  250
1.0        1.0       -0.5       -51.5     0.1000E-101.        0.10
0.0012     0.        0.         0.2000E 10
100.       1.        29.        0.
    1    1   52   32
0.0005     1500000.  0.         113.28E 10
100.       1.
```

```
    0    0    0    0    2    0    1    2    1      0.000025
    1   52    1  152                             3    1
-5.       105.       -55.       55.
    8    7
    1   52    1  152    1
    1   52    1  152    2
0.          1.
    3    0    0    0    2   -1    1    2    0      0.
    1   52    1  152
-5.       105.       -55.       55.
    1   52    1  152    1
    1   52    1  152    2
1.          20.                  13
0.          1.
    3    0    0    0    2   -1    1    2    0      0.
    1   52    1  152
-5.       105.       -55.       55.
    1   52    1  152    1
    1   52    1  152    2
0.          1.5000E 07           36
0.          1.
    0    0    1    0    2    0    1    0    0      0.00000
    1   52    1  152
-50.        200.       -125.      125.
    1   52    1  152    1
    1   52    1  152    2
    2    2    1  152    9
0.          1.         0.         0.
    0    0    0    0    2   -1    1    2    0      0.
    1   52    1  152
-5.       105.       -55.       55.
    1   52    1  152    1
    1   52    1  152    2
1.          20.                  13
0.          1.
      SUBROUTINE SPEC
      COMMON /V1/ R(52),Z(152),DR(52),DZ(152),U(52,152),V(52,152),E(52,
     1152),RHO(52,152),B(52,152)
      COMMON /V6/ TIME,DT,NCYCLE,NMAX,MINDT,MAXDT
      COMMON / V7  / RHOO,VZ,VR,BO,EO,VISCO,PERMO,SIGO,CONDO,CVO,VELOC
     1,PHIO
      COMMON /V15/ STAB,ARFV
      COMMON /V25/ DE(52,177), IOBK(202),IOBL(202),DANGLE(202),IDFN
      REAL R*8
      DATA IKT/0/
      IKT=IKT+1
      IF(IKT.GT.1) GO TO 5
    5 CONTINUE
      IF(NCYCLE.GT.100) STAB=0.25
      IF(NCYCLE.GT.200) STAB=0.50
      IF(NCYCLE.GT.400) STAB=0.75
      J=94
      DO 1 K=36,52
      IF(U(K,J+1).GT.0) GO TO 100
      RHO(K,J)=RHO(K,J+1)
      U(K,J)=-U(K,J+1)
      V(K,J)=V(K,J+1)
      E(K,J)=E(K,J+1)
      GO TO 1
  100 RHO(K,J)=RHOO
      U(K,J)=VZ
      V(K,J)=VR
      E(K,J)=EO
      RETURN
      END
```

```
                PROJECTILE (1/1)
   50  110                1    0   -1    1    1    1    0    0    3
0.          50.         -10.         60.         -10.         180.
  200    5    5   40    1  800
1.          1.          -0.5        -51.5        0.           1.          .75
0.00134                             .1929 E 10
0.          1.          29.         0.
    1    1   52    1
0.00268   80000.                    .51000E 10
0.          1.
    0    0    0    0    2    0    1    2    1     .0004
    1   52    1  112                           3    1
0.          100.        -50.        50.
    8    7
    1   52    1  112    1
    1   52    1  112    2
0.          1.          1.          1.
    3    0    0    0    2   -1    1    2    0     .0015
    1   52    1  112
0.          100.        -50.        50.
    1   52    1  112    1
    1   52    1  112    2
0.          2.501                   13                    1
0.          1.
    0    0    0    0    2   -1    1    2    0     .0015
    1   52    1  112
0.          100.        -50.        50.
    1   52    1  112    1
    1   52    1  112    2
0.          2.501                   13                    1
0.          1.          1.          1.
      NOZZLE FLOW
   25   80    0    0   -1    0    1    1    1    1    0    1    4
0.6900     0.          0.2800     0.6         0.6900     1.30       0.69       2.70
  125   10   10  250    1  250
0.3333E-010.3333E-01-.1667E-01-0.01667  0.0         0.1000E 010.3000E 00
.001314    0.          0.          .19570E+100.
0.          1.          29.         0.
    1    1   27    1
0.015      0.          0.          .19570E+100.          0.          0.
0.          1.

    0    0    0    0    2    0    0    2    1     0.0015
    1   27    1   82                           2    2
-0.5       1.5         -1.         1.
    8    7
    1   27    1   82    1
    1   27    1   82    2
0.          1.          1.          1.
    3    0    0    0    2   -1    0    2    0     0.0015
    1   27    1   82                           2    2
-0.8       1.2         -1.         1.
    1   27    1   82    1
    1   27    1   82    2
0.          2.3                     13
0.          1.          1.          1.
    0    0    0    0    2   -1    0    2
    1   27    1   82
-0.8       1.2         -1.         1.
    1   27    1   82    1
    1   27    1   82    2
0.          2.3                     13
0.          1.          1.          1.
    3    0    0    0    2   -1    0    2    1     .0015
    1   27    1   82                           2    2
-0.8       1.2         -1.         1.
    8    7
    1   27    1   82    1
    1   27    1   82    2
```

```
0.        2.3                13                    1
0.         1.         1.         1.
    0    0    0    0    2   -1    0    2    0     0.0015
    1   27    1   82
-0.8      1.2       -1.         1.
    1   27    1   82    1
    1   27    1   82    2
0.        2.3                13                    1
0.         1.         1.         1.
    3         5         2   -1         2    1     0.0015
    1   27    1   82                        2    2
-0.2      2.7       -2.         0.9
    8    7
    1   27    1   82    1
    1   27    1   82    2
    2    2    1   82    7
    2    2    1   82    8
    2    2    1   82    9
    2    2    1   82   13
    2    2    1   82   14
0.        2.3                13                    1
0.         1.         1.         1.

      FLOW OVER A SEMI-INF CYLN (M=4.5)
   50  125    0    1    0   -1    1    1    1    1    0    0   15
-25.       0.        -25.       1.        -24.75     2.5       -24.30     5.
-23.80     7.5       -22.80     10.       -21.50     12.5      -20.       15.
-17.       18.       -14.       20.7      -11.       22.3      -8.        23.6
-5.        24.2      -2.6       24.6      0.         25.
  400    5    5  200    1  800
1.         1.        -0.5       -51.5     0.         1.        0.6
0.00128    0.        0.         0.1956E 10
100.       1.        29.        0.
    1    1    1  127
0.00128    0.        150000.    1.3210E 10
100.       1.



    0    0    0    0    2    0    0    1    1     0.00010
    1   52    1  127                        2    2
-100.      0.        -100.      0.
    8    7
    1   52    1  127    1
    1   52    1  127    2
0.         1.         1.         1.
    3    0    0    0    2   -1    0    1    0     0.00010
    1   52    1  127
-100.      0.        -100.      0.
    1   52    1  127    1
    1   52    1  127    2
0.        5.0                13
0.         1.


   DETACHED OBLIQUE SHOCK (48 DEG)
   30   95    0    0    1    0    1    1    1    1    0    0    2
0.        5.7       -4.        9.7
  250    2    4  500    1  500
.10        .20       0.         -6.3      0.         1.        .75       0.
.001314    0.        0.         .19570E+100.
0.         1.        29.        0.
    1    1   32    1
.002000    120000.   0.         1.0000E 10
0.         1.
```

```
    0    0    0    0    2    0    0    0    1     .00015
    1   32    1   97                             2    1
-0.5      6.5       -7.        0.
    8    7
    1   32    1   97    1
    1   32    1   97    2
0.         1.         0.         1.
    0    0    0    0    2   -1    0    0    0     .00015
    1   32    1   97
-0.5      6.5       -7.        0.
    1   32    1   97    1
    1   32    1   97    2
1.         4.                   13
0.         1.         0.         1.


    ONE ELECTRODE (BETA=0.)
   14   40    0    1    1    0    1    1    2    1    6    0    4    1
8.0       -0.5       8.0       25.       8.0       25.       8.0       71.
100.       1.       100.       1.       00.          17   26
    1    5    5    1    1    1
1.4       1.4       -0.7      -11.       0.        1.        0.75      0.
0.00128   00000.    0.        0.5000E 10+20000.
10.        1.        29.       0.
    1    1   16   42
0.00128   50000.    0.        0.7500E '0+20000.
10.        1.
    3    0    0    0    2   -1    1    0    0     100.
    1   16    1   42
0.         32.       -16.      16.
    1   16    1   42    1
    1   16    1   42    2
-0.15      0.42                 33
0.         1.         1.         1.
    0    0    0    0    2   -1    3    0    0     100.
    1   16    1   42
0.         32.       -16.      16.
    1   16    1   42    1
    1   16    1   42    2
-0.15      0.42                 33
0.         1.         1.         1.
    0    0    0    0    2    0    1    0    1     .00000005
    1   16    1   42
0.         32.       -16.      16.
   19   20
    1   16    1   42    1
    1   16    1   42    2
0.         1.         1.         1.
    3    0    0    0    2   -1    1    0    0     1250.
    1   16    1   42
0.         32.       -16.      16.
    1   16    1   42    1
    1   16    1   42    2
-0.4      +0.4                  32
0.         1.         1.         1.


   HALL PARAMETER = 5
   14   40    0    1    1    1    1    1    2    1    6    1    4    1
8.        -0.5       8.        25.       8.        25.       8.        41.
100.       1.       1.         1.        0.          17   26
    1    5    5    1    1    1
1.         1.4       -0.5      -11.       0.        1.        0.10      0.
0.00128   0.         0.        0.5000E 1020000.
```

```
0.          1.          29.         0.
    1    1   16   42
0.00128   50000.    0.          0.7500E 1020000.
0.          1.



    0    0    0    0    2   -1    5
    1   16    1   42
-12.5      37.5       -25.       25.
    1   16    1   42    1
    1   16    1   42    2
-0.2       0.70                  33
0.          1.          1.          1.
    0    0    0    0    2   -1    5
    1   16    1   42
-12.5      37.5       -25.       25.
    1   16    1   42    1
    1   16    1   42    2
-10.       80.                   32
0.          1.          1.          1.
    3    0    0    0    2   -1
    1   16    1   42
0.          25.        -12.5      12.5
    1   16    1   42    1
    1   16    1   42    2
-0.3       0.3                   33
0.          1.          1.          1.
    0    0    0    0    2   -1    5
    1   16    1   42
0.          25.        -12.5      12.5
    1   16    1   42    1
    1   16    1   42    2
-0.1       0.35                  33
0.          1.          1.          1.
    0    0    0    0    2    0    0    0    1      1250.
    1   16    1   42
0.          25.        -12.5      12.5
   26   27
    1   16    1   42    1
    1   16    1   42    2
0.          1.          1.          1.
    0    0    0    0    2    0    0    0    1      0.00000005
    1   16    1   42
0.          25.        -12.5      12.5
   19   20
    1   16    1   42    1
    1   16    1   42    2
0.          1.          1.          1.
    3    0    0    0    2   -1
    1   16    1   42
0.          25.        -12.5      12.5
    1   16    1   42    1
    1   16    1   42    2
-10.       80.                   32
0.          1.          1.          1.
    0    0    0    0    2   -1
    1   16    1   42
0.          25.        -12.5      12.5
    1   16    1   42    1
    1   16    1   42    2
-10.       80.                   32
0.          1.          1.          1.
      FUNCTION BETA(I,J,IHALF,JHALF)
      BETA=5.
      RETURN
      END
```

```
   THREE ELECTRODES (BETA=2.)
   30  103    0    1    1    1    1    1    2    1    1    1    4   10
14.        -0.5       14.        25.        14.        50.        14.        105.
10.        10.        75.        25.        00.           24   82
    1    1   10    1    1    1
1.0        1.0        -0.5       -16.       0.         1.         0.10       0.
0.00128    00000.     0.         0.5000E 1020000.
0.         1.         29.        0.
    1    1   32  105
0.00128    50000.     0.         0.7500E 1020000.
0.         1.



    0    0    0    0    2    0    1    0    1      1250.
    1   32    1  105
5.         60.        -27.5      27.5
   26   27
    1   32    1  105    1
    1   32    1  105    2
0.         1.         1.         1.
    0    0    0    0    2   -1    0    0    0      100.
    1   32    1  105
5.         60.        -27.5      27.5
    1   32    1  105    1
    1   32    1  105    2
0.         1.0                   33
0.         1.         1.         1.
    0    0    0    0    2   -1    5    0    0      100.
    1   32    1  105
-20.       80.        -50.       50.
    1   32    1  105    1
    1   32    1  105    2
0.         2.                    33
 0#          C8        1.         1.
    3    0    0    0    2   -1    1    0    0      100.
    1   32    1  105
5.         60.        -27.5      27.5
    1   32    1  105    1
    1   32    1  105    2
0.         1.0                   33
0.         1.         1.         1.
      FUNCTION BETA(I,J,IHALF,JHALF)
      BETA=2.
      RETURN
      END


   SHOCK INDUCED EDDY CURRENTS
   24   70    0    1   -1    0   -1    1    2    1    0    0    4    1
10.5       -0.5       10.5       25.        10.5       25.        10.5       71.
100.       1.         100.       10.        00.           17   26
   30    5    5   30    1   60
1.0        1.0        -0.5       -13.       0.         1.         0.75       0.
0.00128    00000.     0.         0.5000E 10+20000.
10.        1.         29.        0.
    1    1   26   72
0.00128    50000.     0.         0.7500E 10+20000.
10.        1.
    1    1   26    1
0.0250     50000.     0.         0.7500E 10+20000.
10.        1.
```

```
    0    0    0    0    2   -1    5
    1   26    1   72
0.        70.       -70.       0.
    1   26    1   72    1
    1   26    1   72    2
   12   12    1   72   13
-0.15     0.42              33
0.        1.
    0    0    0    0    2   -1    3    0    0     1250.
    1   26    1   72
0.        25.       -12.5      12.5
    1   26    1   72    1
    1   26    1   72    2
-0.15     0.42              33
0.        1.         0.00015   0.00015
    0    0    0    0    2    0    1    0    1     1250.
    1   26    1   42    1   26    1   72
0.        25.       -12.5      12.5
   26   27
    1   26    1   42    1
    1   26    1   42    2
0.        1.
    3    0    0    0    2   -1    1    0    0     1250.
    1   26    1   42    1   26    1   72
0.        25.       -12.5      12.5
    1   26    1   42    1
    1   26    1   42    2
-0.15     0.42              33
0.        1.
    0    0    0    0    2   -1    1    0    0     100.
    1   16    1   42
0.        25.       -12.5      12.5
    1   16    1   42    1
    1   16    1   42    2
-0.15     0.42              33
0.        1.
    2    0    1    0    2   -1    1    0    0     1250.
    1   16    1   72
0.        70.       -65.       5.
    1   16    1   72    1
    1   16    1   72    2
   12   12    1   72    9
1.55      3.                  13
0.        1.
    2    0    1    0    2   -1    1    0    0     1250.
    1   16    1   72
0.        70.       -65.       5.
    1   16    1   72    1
    1   16    1   72    2
    2    2    1   72   14
-0.15     0.42              33
0.        1.
      SUBROUTINE SPEC
      COMMON /V1/ R(52),Z(152),DR(52),DZ(152),U(52,152),V(52,152),E(52,1  A  11
     152),RHO(52,152),B(52,152)
      COMMON /V4/ IMAX,JMAX,IP1,JP1,IP2,JP2,IAXI,IPTSF,ISYM(4)
      REAL*8 R,RIPH,RIMH,RIP3H,RTOP
      DO 1 K=1,IP2
      DO 1 J=1,JP2
      V(K,J)=0.
      B(K,J)=20000.
    1 CONTINUE
```

```
      RETURN
      END
      FUNCTION BETA(I,J,IHALF,JHALF)
      COMMON / V7  / RHOO,VZ,VR,BO,EO,VISCO,PERMO,SIGO,CONDO,CVO,VELOC
     1,PHIO
      BETA=0.
      RETURN
      END
      FUNCTION GAMM(I,J)
      GAMM=1.15
      RETURN
      END
      FUNCTION SIG (I,J,IHALF,JHALF,IN)
      COMMON /V14/ NMAGN,NTHRM,NVISC,NCONV,IPOT
      SIG=10.**(-10)
      NMAGN=99999
      RETURN
      END
```

C.6 PROGRAM SUGGESTIONS

The most expeditious approach to learning the function of this program and avoiding the numeroud pit-falls which discourage further use is to start with one of the many test cases discussed in C.5 and in stages, refine the input to suit the particular needs of the problem in question.

The major and most frequent error that occurs is numerical instability. It is easily detected by observing that velocities and energy grow exponentially in time; the density vanishes or pressures and temperatures become negative. The run will usually terminate abnormally and give various diagnostics. The source of the instability is an excessively large time step. The simple procedure for correcting this error is to reduce the time step through the input parameter STAB (DT = DT (Min) x STAB), which is normally set to 0.75. Reducing STAB by 10 to 50% may in most circumstances result in a stable calculation.

C.7 HULL DIFFERENCE MINORITY REPORT

The development of methodology employed in this program was based strictly on comments prefacing the HULL computer logic. Written by one of the principal authors, Richard E. Durrett, it is entitled "The Hull Difference Minority Report." From this explicit 5-page summary of the HULL technique, a 6500 card FORTRAN IV computer program, the subject of this report, was developed!

MINORITY REPORT ON HULL

THE HULL DIFFERENCE METHOD

THE HULL SYSTEM EMPLOYS THE STANDARD SHELL DIFFERENCE METHOD OR A MORE STABLE, FULLY SECOND ORDER ACCURATE METHOD DEVELOPED BY CAPTAIN MATUSKA AT THE AIR FORCE WEAPONS LABORATORY (AFWL). THESE ARE REFERRED TO AS METHODS 1 AND 2 RESPECTIVELY.

THE SHELL DIFFERENCE METHOD (METHOD 1) IS DETAILED IN AFWL TR 66-141. METHOD 2 IS PRESENTED BELOW.

THE METHOD IS APPLIED TO THE EQUATIONS DESCRIBING THE BEHAVIOR OF A COMPRESSIBLE, NONCONDUCTING, INVISCID FLUID. THE EQUATIONS ARE THOSE DESCRIBING

CONSERVATION OF MASS

D(RHO)+RHO*DIV(U#)=0 (1)

CONSERVATION OF MOMENTUM

RHO*D(U#)+GRAD(P)=-RHO*G# (2)

CONSERVATION OF ENERGY

RHO*D(E)+DIV(P*U#)=-RHO*U#*G# (3)

ALONG WITH THE EQUATION OF STATE

P=P(RHO,I) (4)

WHERE

D IS THE LAGRANGIAN DERIVATIVE WITH RESPECT TO TIME

DIV IS THE VECTOR DIVERGENCE

GRAD IS THE GRADIENT VECTOR OPERATOR

RHO=MATERIAL DENSITY (GM/CM**3)

P=PRESSURE (DYNES/CM**2)

I=INTERNAL SPECIFIC ENERGY (ERGS/GM)

U#=FLUID VELOCITY (CM/SEC)

E=I+U#*U#/2 (ERGS/GM)

G#=ACCELERATION DUE TO GRAVITY (CM/SEC**2)

T=TIME (SEC)

AND THE SPECIAL SYMBOL # IS USED TO INDICATE A VECTOR QUANTITY. THE MULTIPLICATION SYMBOL (*) BETWEEN VECTORS INDICATES THE DOT PRODUCT.

EQUATIONS 1 THRU 3 ARE APPROXIMATED BY FINITE-DIFFERENCES AND ARE SOLVED EXPLICITLY OVER A DISCRETE TIME INTERVAL DT IN TWO PHASES. THE FIRST PHASE CONSIDERS THE SOLUTION TO EQUATIONS 2 AND 3, WHILE THE SECOND PHASE TREATS EQUATION 1 IN A MANNER WHICH CAUSES DISSIPATION OF KINETIC ENERGY INTO INTERNAL ENERGY, PRINCIPALLY IN THE REGION OF LARGE VELOCITY GRADIENTS. THIS ALLOWS THE CALCULATION OF LARGE DISCONTINUITIES SUCH AS SHOCKS.

THE METHOD WILL BE ILLUSTARTED FOR THE CASE OF TWO-DIMENSIONAL AXISYMMETRIC CYLINDRICAL COORDINATES. EQUATIONS 1 THRU 3 CAN THEN BE WRITTEN AS

D(RHO)+RHO*(1/R*PDR(R*U)+PDZ(V))=0 (5)

RHO*D(U)+PDR(P)=0 (6)

RHO*D(V)+PDZ(P)=-RHO*G (7)

RHO*D(E)+1/R*PDR(R*P*U)+PDZ(P*V)=-RHO*V*G (8)

WHERE

R=RADIAL COORDINATE

Z=AXIAL COORDINATE

PDR=PARTIAL DERIVATIVE WITH RESPECT TO THE RADIAL COORDINATE

PDZ=PARTIAL DERIVATIVE WITH RESPECT TO THE AXIAL COORDINATE

U=COMPONENT OF U# IN THE RADIAL DIRECTION

V=COMPONENT OF U# IN THE AXIAL DIRECTION.

IN ESTABLISHING FINITE DIFFERENCE ANALOGS TO EQUATIONS 5 THRU 8 WE CONSIDER A DISCRETE SUBSET OF F(R,Z,T) BY DEFINING

F(I,J,N)=F(R(I),Z(J),T(N))

WHERE R(I), Z(J), AND T(N) ARE PARTICULAR VALUES OF R, Z, AND T RESPECTIVELY, AND THE I, J, AND N ASSUME INTEGER VALUES IN THE RANGE 1 TO IMAX FOR I, 1 TO JMAX FOR J, AND 0 TO NMAX FOR N. THE R(I) AND Z(J) ARE DEFINED IN TERMS OF A GIVEN SET OF DR(I) AND DZ(J) SUCH THAT

R(I)=R(0)+(SUM,K=1,I-1,(DR(K)))+DR(I)/2 FOR I=2,...,IMAX

R(1)=R(0)+DR(1)/2

Z(J)=Z(0)+(SUM,K=1,J-1,(DZ(K)))+DZ(J)/2 FOR J=2,...,JMAX

Z(1)=Z(0)+DZ(1)/2

WHERE R(0) AND Z(0) HAVE SOME SPECIFIED VALUES.

THE HYDRODYNAMIC VARIABLES RHO, U, V, AND I (INTERNAL SPECIFIC ENERGY) ARE DEFINED FOR EACH SET OF COORDINATES (I,J) AT A PARTICULAR TIME T(N). THE PRESSURE P(I,J,N) IS DEFINED AT EACH POINT BY THE EQUATION OF STATE (EQUATION 4).

INTERPOLATED VALUES OF THE HYDRODYNAMIC VARIABLES OF THE FORM F(I+1/2,J,N), F(I,J+1/2,N), OR F(I,J,N+1/2), OR SIMILAR FORMS, ARE DEFINED IN TERMS OF THE F(I,J,N). IN GENERAL

F(I+1/2,J,N)=(F(I+1,J,N)+F(I,J,N))/2

AND

F(I,J+1/2,N)=(F(I,J+1,N)+F(I,J,N))/2.

THIS DEFINITION WILL APPLY EXCEPT WHERE EXPLICITLY NOTED.

PHASE I

IN METHOD 2 THE FINITE DIFFERENCE ANALOGS TO EQUATIONS 6 THRU 8 ARE CHOSEN AS

U(I,J,N+1)=U(I,J,N)-DT*(P(I+1/2,J,N+1/2)-P(I-1/2,J,N+1/2))/(RHO(I,J,N)*DR(I)) (9)

V(I,J,N+1)=V(I,J,N)-DT*(P(I,J+1/2,N+1/2)-P(I,J-1/2,N+1/2))/(RHO(I,J,N)*DZ(J))-DT*G(J) (10)

E(I,J,N+1)=E(I,J,N)-DT/RHO(I,J,N)*((R(I+1/2)*P(I+1/2,J,N+1/2)*U(I+1/2,J,N+1/2)-R(I-1/2)*P(I-1/2,J,N+1/2)*U(I-1/2,J,N+1/2))/(R(I)*DR(I))+(P(I,J+1/2,N+1/2)

Figure C.31 Synopsis of HULL Code

*V(I,J+1/2,N+1/2)-P(I,J-1/2,N+1/2)*V(I,J-1/2,N+1/2))
/DZ(J))-DT*V(I,J,N+1)*G(J) (11)

WHERE

DT=T(N+1)-T(N)

R(I+1/2)=R(I)+DR(I)/2

R(I-1/2)=R((I-1)+1/2)

Z(J+1/2)=Z(J)+DZ(J)/2

Z(J-1/2)=Z((J-1)+1/2)

G(J)=VALUE OF G AT Z(J).

ALL THE VALUES APPEARING IN EQUATIONS 9 THRU 11 ARE IMMEDIATELY KNOWN EXCEPT THE TIME ADVANCED (N+1/2) VALUES FOR PRESSURE AND VELOCITY. THESE TIME ADVANCED VALUES ARE USED SO THAT THE APPROXIMATIONS TO THE PARTIAL DERIVATIVES APPEARING IN EQUATIONS 6 THRU 8 MAY BE CENTERED IN TIME AND SPACE. IN THE CASE WHERE

DR(I)=CONSTANT FOR I=1,...,IMAX

AND

DZ(J)=CONSTANT FOR J=1,...,JMAX

THIS PRODUCES A FULLY SECOND ORDER ACCURATE DIFFERENCE METHOD. IN A REGION WHERE THE DR(I) AND DZ(J) ARE NOT CONSTANT THE SECOND ORDER ACCURACY IS LOST. THIS ADVERSELY AFFECTS THE STABILITY OF THE FIRST PHASE CALCULATION. THE AMOUNT OF INSTABILITY WHICH MAY BE OBTAINED IS RELATED TO THE MAGNITUDE OF THE INCREMENTAL CHANGES IN DR(I) AND DZ(J).

MOST OF THE COMPUTATIONS IN THE FIRST PHASE ARE EXPENDED IN OBTAINING THE TIME ADVANCED VALUES FOR PRESSURE AND VELOCITY. THE TIME ADVANCED VELOCITIES ARE OBTAINED BY DIFFERENCING EQUATIONS 6 AND 7 AS

U(I+1/2,J,N+1/2)=U(I+1/2,J,N)-DT/(2*RHO(I+1/2,J,N+1/2))
*((P(I+1,J,N)-P(I,J,N))/(R(I+1)-R(I))) (12)

V(I,J+1/2,N+1/2)=V(I,J+1/2,N)-DT/(2*RHO(I,J+1/2,N+1/2))
*((P(I,J+1,N)-P(I,J,N))/(Z(J+1)-Z(J)))
-G(J+1/2)*DT/2 (13)

WHERE

G(J+1/2)=(G(J)+G(J+1))/2.

THE TIME ADVANCED DENSITIES APPEARING IN EQUATIONS 12 AND 13 ARE OBTAINED BY DIFFERENCING EQUATION 5 AS

RHO(I+1/2,J,N+1/2)=RHO(I+1/2,J,N)*(1-DT/(2*R(I+1/2))*(R(I+1)
*U(I+1,J,N)-R(I)*U(I,J,N))/(R(I+1)-R(I)))
(14)

RHO(I,J+1/2,N+1/2)=RHO(I,J+1/2,N)*(1-DT/2*(V(I,J+1,N)-V(I,J,N))
/(Z(J+1)-Z(J))) (15)

WHERE

RHO(I+1/2,J,N)=(M(I,J,N)+M(I+1,J,N))/(PI*(R(I+1/2)**2
-R(I-1/2)**2)*DZ(J))

RHO(I,J+1/2,N)=(M(I,J,N)+M(I,J+1,N))/(PI*(R(I+1/2)**2
-R(I-1/2)**2)*(DZ(J)+DZ(J+1)))

AND THE MASS ASSOCIATED WITH A POINT (I,J,N) IS DEFINED BY

M(I,J,N)=RHO(I,J,N)*(PI*(R(I+1/2)**2-R(I-1/2)**2)*DZ(J))

WHERE PI=3.14159... AND R(I+3/2)=R((I+1)+1/2).

THE TIME ADVANCED PRESSURE APPEARING IN EQUATIONS 9 THRU 11 REQUIRES A LITTLE MORE EFFORT. FIRST AN ALTERNATIVE ENERGY EQUATION CAN BE OBTAINED FROM EQUATIONS 2 AND 3 AS

RHO*D(I)+P*DIV(U#)=0. (16)

AN EFFECTIVE GAMMA CAN BE DEFINED BY

GAMMA=1+P/(RHO*I). (17)

WE WILL ASSUME FOR THE PURPOSES OF CALCULATING A HALF TIME STEP ADVANCED PRESSURE, WHICH IN TURN IS USED IN APPROXIMATING THE PARTIAL DERIVATIVES IN EQUATIONS 9 THRU 11, THAT THE LAGRANGIAN DERIVATIVE WITH RESPECT TO TIME OF GAMMA IS SMALL AND CAN BE IGNORED. IN APPLICATION IT IS ONLY REQUIRED THAT THE CHANGE IN GAMMA AT A PARTICULAR POINT BE SMALL OVER A TIME OF DT/2.

TAKING THE LAGRANGIAN DERIVATIVE WITH RESPECT TO TIME IN EQUATION 17 AND USING EQUATIONS 1 AND 16 WE CAN WRITE

D(P)+GAMMA*P*DIV(U#)=0. (18)

EQUATION 18 IS USED TO OBTAIN TIME ADVANCED PRESSURES GIVEN BY

P(I+1/2,J,N+1/2)=P(I+1/2,J,N)*(1-DT*GAMMA(I+1/2,J,N)*(R(I+1)
*U(I+1,J,N)-R(I)*U(I,J,N))/(2*R(I+1/2)*(R(I+1)
-R(I))))

P(I,J+1/2,N+1/2)=P(I,J+1/2,N)*(1-DT*GAMMA(I,J+1/2,N)
(V(I,J+1,N)-V(I,J,N))/(2(Z(J+1)-Z(J))))

WHERE GAMMA IS OBTAINED FROM EQUATION 17 AS

GAMMA(I+1/2,J,N)=1+P(I+1/2,J,N)/(RHO(I+1/2,J,N)*I(I+1/2,J,N))

GAMMA(I,J+1/2,N)=1+P(I,J+1/2,N)/(RHO(I,J+1/2,N)*I(I,J+1/2,N)).

ALL QUANTITIES NEEDED TO SOLVE EQUATIONS 9, 10, AND 11 ARE NOW DEFINED. SOLUTION OF THESE EQUATIONS WILL COMPLETE A SECOND ORDER ACCURATE LAGRANGIAN CALCULATION. THE NEXT STEP WOULD NORMALLY BE THAT OF TRANSPORTING MESH VERTICES. INSTEAD WE CHOOSE TO FLUX THE HYDRODYNAMIC QUANTITIES TO RETAIN THE ORIGINAL MESH CONFIGURATION. THIS CALCULATION IS DONE IN PHASE II.

PHASE II

CHANGES IN DENSITY ARE COMPUTED IN PHASE II BY CALCULATING A MASS FLUX BETWEEN MESH POINTS AND THEN TRANSPORTING THE APPROPRIATE AMOUNT OF MASS FROM POINT TO POINT. THE TRANSPORTED MASS CARRIES WITH IT A PROPORTIONATE AMOUNT OF INTERNAL ENERGY AND MOMENTUM. THE VELOCITIES AND SPECIFIC INTERNAL ENERGY ARE THEN REDEFINED AT EACH MESH POINT BY CONSERVING MOMENTUM AND TOTAL ENERGY AT THAT POINT.

THE MASS FLUX BETWEEN MESH POINTS IS DEFINED AS THE PRODUCT OF THE INTERPOLATE VELOCITY, THE DENSITY AS DEFINED BY SOLUTION OF EQUATION 1, THE INTERMEDIATE CROSS SECTIONAL AREA, AND THE TIME STEP. THE EQUATIONS ARE

MF(I+1/2,J,N+1)=U(I+1/2,J,N+1)*RHO(I+1/2,J,N+1)*2*PI*R(I+1/2)
*DZ(J)*DT

MF(I,J+1/2,N+1)=V(I,J+1/2,N+1)*RHO(I,J+1/2,N+1)*2*PI*R(I)*DR(I)
*DT

WHERE THE TIME ADVANCED DENSITIES ARE OBTAINED BY DIFFERENCING EQUATION 5 AS

RHO(I+1/2,J,N+1)=RHO(ID,J,N)*(1-DT/R(I+1/2)*(R(I+1)
*U(I+1,J,N+1)-R(I)*U(I,J,N+1))/(R(I+1)-R(I)))

RHO(I,J+1/2,N+1)=RHO(I,JD,N)*(1-DT*(V(I,J+1,N+1)-V(I,J,N+1))
/(Z(J+1)-Z(J)))

Figure C.31 Continued

```
WHERE

      ID=I    IF U(I+1/2,J,N+1)  GT  0
        =I+1  IF U(I+1/2,J,N+1)  LT  0

      JD=J    IF V(I,J+1/2,N+1)  GT  0
        =J+1  IF V(I,J+1/2,N+1)  LT  0.

THIS IS THE CLASSICAL DONOR CELL DIFFERENCING TECHNIQUE.  THE MOST
OBVIOUS ADVANTAGES OF THIS TECHNIQUE ARE ITS RIGID NUMERICAL
CONSERVATION AND ITS STABILITY.  THIS SCHEME ALSO INSURES THAT MORE
MATERIAL CAN NOT BE REMOVED FROM A POINT THAN IS PRESENT.

    HULL HAS A CONTINUOUS REZONE CAPABILITY.  WHEN THIS IS EMPLOYED
THE INTERPOLATED VELOCITIES APPEARING IN THE MASS FLUX EQUATIONS ARE
REPLACED BY

      U(I+1/2,J,N+1)-UR(I+1/2,J,N+1)

      V(I,J+1/2,N+1)-VR(I,J+1/2,N+1)

WHERE UR AND VR ARE THE INTERPOLATED GRID VELOCITIES (DETERMINED
ARBITRARILY BY HOW FAST ONE WISHES TO TRANSPORT THE COORDINATE GRID).

THE CORRESPONDING MOMENTUM FLUXES ARE

      UF(I+1/2,J,N+1)=MF(I+1/2,J,N+1)*U(ID,J,N+1)

      VF(I+1/2,J,N+1)=MF(I+1/2,J,N+1)*V(ID,J,N+1)

      UF(I,J+1/2,N+1)=MF(I,J+1/2,N+1)*U(I,JD,N+1)

      VF(I,J+1/2,N+1)=MF(I,J+1/2,N+1)*V(I,JD,N+1)

AND THE ENERGY FLUXES ARE

      EF(I+1/2,J,N+1)=MF(I+1/2,J,N+1)*E(ID,J,N+1)

      EF(I,J+1/2,N+1)=MF(I,J+1/2,N+1)*E(I,JD,N+1).

    WHEN THESE QUANTITIES ARE FLUXED FINAL VALUES FOR MASS, DENSITY,
VELOCITY, AND ENERGY ARE COMPUTED BY

      M(I,J)=M(I,J,N)+MF(I-1/2,J,N+1)+MF(I,J-1/2,N+1)
                     -MF(I+1/2,J,N+1)-MF(I,J+1/2,N+1)

      RHO(I,J)=M(I,J)/(PI*(R(I+1/2)**2-R(I-1/2)**2)*DZ(J))

      U(I,J)=(U(I,J,N+1)*M(I,J,N)+UF(I-1/2,J,N+1)+UF(I,J-1/2,N+1)
             -UF(I+1/2,J,N+1)-UF(I,J+1/2,N+1))/M(I,J)

      V(I,J)=(V(I,J,N+1)*M(I,J,N)+VF(I-1/2,J,N+1)+VF(I,J-1/2,N+1)
             -VF(I,J+1/2,N+1)-VF(I+1/2,J,N+1))/M(I,J)

      I(I,J)=(E(I,J,N+1)*M(I,J,N)+EF(I-1/2,J,N+1)+EF(I,J-1/2,N+1)
             -EF(I+1/2,J,N+1)-EF(I,J+1/2,N+1)-(U(I,J)**2+V(I,J)**2)
             *M(I,J)/2)/M(I,J)

      E(I,J)=I(I,J)+(U(I,J)**2+V(I,J)**2)/2

WHERE THE LACK OF A TIME SPECIFICATION INDICATES FINAL VALUES FOR THIS
TIME STEP.
```

Figure C.31 Continued

```
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C     XXXXXXXXXXXXXXXXXXXXXXXX IBM 370 VERSION XXXXXXXXXXXXXXXXXXXXXXXX
C     XXXXXXXXXXXXXXXXXXXXXXXXX CALCOMP PLOTTER XXXXXXXXXXXXXXXXXXXXXXXXX
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C     ------------------------------------------------------------------
C
C     I                                                                I
C     I                                                                I
C     I         A NUMERICAL PROCEDURE FOR PREDICTING TRANSIENT         I
C     I          SHOCK, BOUNDARY LAYER AND MAGNETOHYDRODYNAMIC         I
C     I                          PHENOMENA                             I
C     I                    BY LAURENCE ALAN FELDMAN                    I
C     I                       FEB 1975-JUNE 1978                       I
C     I                 AUBURN UNIVERSITY, AUBURN, AL.                 I
C     I          UNIV OF TENN SPACE INSTITUTE, TULLAHOMA, TENN.        I
C     I                    ARNOLD AFS (AEDC), TENN.                    I
C     I                                                                I
C     I                       COPYRIGHT: JUNE, 1978                    I
C     I                                                                I
C     I                                                                I
C     ------------------------------------------------------------------
C
C
C     ********************************************************************
C     ****** COMPLETE DOCUMENTATION AND USER'S MANUAL IN ****************
C     ********************** AEDC TR-77-105 ******************************
C     ********************************************************************
C     ********************************************************************
C     LABELLED COMMON BLOCK "CARRAY" CONTROLS THE GRID RESOLUTION AND
C     THUS, THE SIZE OF CENTRAL MEMORY. IF THE PROGRAM IS TOO LARGE,
C     REDUCE THE DIMENSIONS (RESTRICTING THE GRID SIZE) OF THE VARIABLE
C     ARRAYS LISTED IN "CARRAY".
C     ********************************************************************
C     ********************************************************************
C     ON THE IBM 360 OR 370 MODELS, DOUBLE PRECISION MUST BE USED
C     FOR THE FOLLOWING VARIABLES:   R,RIPH,RIMH,RIP3H AND RD.
C     SIMPLY INSERT INTO ALL SUBROUTINES THAT EMPLOY LABELLED COMMON
C     BLOCK "CARRAY" THE FOLLOWING STATEMENT (BEGINNING IN COLUMN 7)
C     REAL*8 R,RIPH,RIMH,RIP3H,RD  **** THIS CARD COMES AFTER THE LAST
C     COMMON OR DIMENSION STATEMENT.
C     ********************************************************************
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C     XXXXXXXXXXXXXXXXXXXXXXXXX  MAIN PROGRAM  XXXXXXXXXXXXXXXXXXXXXXXXX
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C
C
C     ********************************************************************
C     GRID SET UP FOR A MAXIMUM OF 45 X 225 CELLS. INCREASING THE RESOL-
C     UTION BEYOND THESE VALUES WILL REQUIRE AN INCREASE IN THE APPROP-
C     RIATE ARRAYS.
C     ********************************************************************
C
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2
      COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D
     1ZO,DRO,IGRAPH(225),NBOUND
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM
     1,NVECT,NPDIM
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF
      COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTOL,TZERO,T
```

```
      REAL*8 R,RD                                                       64
C                                                                       65
C                                                                       66
C     FOR IBM 370, REPLACE WITH "CALL DRIVER"                           67
      CALL DRIVER                                                       68
      CALL SECOND (A)                                                   69
      WRITE (6,10) A                                                    70
      CALL PLOTTE                                                       71
      CALL SECOND (A)                                                   72
      WRITE (6,10) A                                                    73
      CALL EXIT                                                         74
C                                                                       75
C                                                                       76
C                                                                       77
   10 FORMAT (12H  CP SECONDS,2X,E12.4)                                 78
      END                                                               79
      SUBROUTINE DRIVER                                                 80
C                                                                       81
C                                                                       82
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   83
C     EXECUTIVE ROUTINE CALLING HYDRO: PHASE I AND II, THERMAL CONDUCT-  84
C     ION, MAGNETIC INDUCTION, TIME-STEP, INPUT/OUTPUT AND GRAPH        85
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   86
C                                                                       87
C                                                                       88
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 89
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                              90
      COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH     91
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                          92
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 93
      COMMON /GRAVTY/ GC,GR,GZ                                          94
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX           95
      COMMON/CGRID/R(45),RO(45),Z(225),DR(45),DZ(225),XO(45),ZMIN,RMIN,D 96
     1ZO,DRO,IGRAPH(225),NBOUND                                         97
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IOFN,IPTSF           98
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM 99
     1,NVECT,NPDIM                                                      100
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX 101
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225 102
     1),DIAG(225),SUP(225),CONST(225)                                   103
      COMMON/CSTORE/RHOF(2,225),UF(2,225),VF(2,225),EF(2,225),MFA(225), 104
     1UA(225),VA(225),UFA(225),VFA(225),EFA(225),PA(225)                105
      COMMON/CSTRSS/TRRA(225),TZZA(225),TOOA(225),TRZA(225),VISC,VISCO  106
      COMMON /CMAGN/BFA(225),BZZA(225),BZFA(225),BF(2,225),BFR(2,225),  107
     1BFZ(2,225)                                                        108
      COMMON/ETRODE/ANODE(225),CATHOD(225)                              109
      REAL*8 R,RD                                                       110
C                                                                       111
C                                                                       112
      KL=0                                                              113
      NFLD=0                                                            114
      NCOND=0                                                           115
      NVISC=1000                                                        116
      IOFN=0                                                            117
      READ (5,90) (TITLE(I),I=1,15),IPRN                                118
      WRITE (6,100) (TITLE(I),I=1,15)                                   119
      IF (IPRN.EQ.9) GO TO 80                                           120
      NCYCLE=0                                                          121
      DT=10.**(-12)                                                     122
      IPR=1                                                             123
      GZ=0.                                                             124
      GR=0.                                                             125
C     ********************************************************************126
C     CALLING FOR INPUT AND SETTING INITIAL AND BOUNDARY CONDITIONS     127
```

```
C     ****************************************************************      128
      CALL INPUT                                                            129
      NPOT=IPOT                                                             130
      IPRNT=IPRN                                                            131
   10 CALL BOUND                                                            132
      CNPRNT=NPRN                                                           133
      CNPRNT=CNPRNT/10.                                                     134
      IF (CNPRNT.GT.1) IPR=CNPRNT                                           135
      IF (NPOT.LT.IPOT.OR.IPOT.EQ.0) GO TO 30                               136
C     ****************************************************************      137
C     ********** INITIAL CONVERGENCE OF CURRENT STREAM FUNCTION **********   138
C     ************************** OR POTENTIAL ************************      139
C     ****************************************************************      140
      IDFN=1                                                                141
      CALL BOUND                                                            142
      KLMAX=DPOT                                                            143
      IF (NCYCLE.EQ.0) KLMAX=BASEP                                          144
      DO 20 KJ=1,KLMAX                                                      145
      KL=KL+1                                                               146
      WRITE (6,110) KL                                                      147
      CALL EFIELD                                                           148
   20 CONTINUE                                                              149
   30 CONTINUE                                                              150
C     ****************************************************************      151
C     ************************** OUTPUT AND PLOT DATA ********************   152
C     ****************************************************************      153
      IF (MOD(NCYCLE,IPR).EQ.0) WRITE (6,150) TIME,DT,NCYCLE                154
      IF (MOD(NCYCLE,NPRN).EQ.0.) CALL OUTPUT                               155
      IF (MOD(NCYCLE,NPLOT).EQ.0.AND.NPDIM.GT.0) CALL GRAPH                 156
      IF (NCYCLE.GT.NMAX) GO TO 70                                          157
C     ****************************************************************      158
C     ************************** PHASE I (HYDRO) *************************   159
C     ****************************************************************      160
      CALL HULLP1                                                           161
C     ****************************************************************      162
C     ********** COMPUTING TIME STEP AND BOUNDARY CONDITIONS **********      163
C     ****************************************************************      164
      CALL TMESTP                                                           165
      CALL BOUND                                                            166
      IF (NCOND.LT.NTHRM) GO TO 50                                          167
C     ****************************************************************      168
C     ********************** THERMAL CONDUCTION **********************      169
C     ****************************************************************      170
      NCOND=0                                                               171
      IDFN=2                                                                172
      CALL BOUND                                                            173
      WRITE (6,120)                                                         174
      CALL TEMDIF                                                           175
      DO 40 K=2,KP1                                                         176
      DO 40 J=2,JP1                                                         177
      ENERGY=E(K,J)-0.5*(U(K,J)**2+V(K,J)**2)                               178
      E(K,J)=CV(K,J,0,0)*DE(K,J)-ENERGY+0.5*(U(K,J)**2+V(K,J)**2)           179
   40 CONTINUE                                                              180
   50 CONTINUE                                                              181
C     ****************************************************************      182
C     ********************** MAGNETIC INDUCTION **********************      183
C     ****************************************************************      184
      IF (NFLD.LT.NMAGN) GO TO 60                                           185
      NFLD=0                                                                186
      IDFN=1                                                                187
      CALL BOUND                                                            188
      WRITE (6,130)                                                         189
      CALL DFSN                                                             190
   60 CONTINUE                                                              191
```

```
C     ************************************************************************
C     ********************** PHASE II (CONVECTION) ***************************
C     ************************************************************************
      CALL HULLP2
      IDFN=0
      TIME=TIME+DT
      NCYCLE=NCYCLE+1
      NFLD=NFLD+1
      NCOND=NCOND+1
      NPOT=NPOT+1
      IF (NPOT.GT.IPOT) NPOT=1
      CALL SECOND (A)
      IF (MOD(NCYCLE,IPR).EQ.0) WRITE (6,140) A
      IPRN=0
      IF (MOD(NCYCLE,NPRN).EQ.0) IPRN=IPRNT
      GO TO 10
   70 CONTINUE
   80 RETURN
C
C
C
   90 FORMAT (15A4,19X,I1)
  100 FORMAT (1H1,///,15X,15A4)
  110 FORMAT (29H PHI OR PSI ITERATIONS NUMBER,5X,I3)
  120 FORMAT (26H  TEMPERATURE ITERATION   )
  130 FORMAT (35H  MAGNETIC INDUCTION ITERATION     )
  140 FORMAT (12H  CP SECONDS,2X,E12.4)
  150 FORMAT (6X,100(1H*),/,20X,7HTIME = ,E12.4,5X,5HDT = ,E12.4,5X,9HNC
     1YCLE = ,I4,/,6X,100(1H*))
      END
      SUBROUTINE INPUT
C
C
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C     CARD AND TAPE INPUT DATA
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C
      COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX
      COMMON /GRAVTY/ GC,GR,GZ
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D
     1ZO,DRO,IGRAPH(225),NBOUND
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF
      COMMON/CSTRSS/TRRA(225),TZZA(225),TODA(225),TRZA(225),VISC,VISCO
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM
     1,NVECT,NPOIM
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225
     1),DIAG(225),SUP(225),CONST(225)
      COMMON /CTAPE/ IRST
      DIMENSION BLAYER(9), ELECT(9)
      REAL MW,MINDT,MAXDT
      REAL*8 R,RD
      DATA BFT,BFR,BFZ,BPHI/0.,0.,0.,0./
      DATA BLAYER,ELECT/4H  IN,4HVISC,4HID  ,4H  LA,4HMINA,4HR   ,4H TUR
     1,4HBULE,4HNT  ,4H   N,4HO EM,4HF   ,4HMG I,4HNDUC,4HTION,4HPOND,4H
     2ERMO,4HTIVE/
C
C
```

```
C     ****************************** UNITS ******************************
C     RHO      GM CM-3          K        GM CM SEC-3 K-1 B        GAUSS
C     ***********************************************************************
C     U        CM SEC-1         CV       ERG GM-1 K-1
C     ***********************************************************************
C     R        CM               T        DYNE-CM
C     ***********************************************************************
C     VISC     GM CM-1 SEC-1 (PS)
C     ***********************************************************************
C     B = GAUSS (GM/ABCOUL /SEC ) = 10-4 WEBER/METER2
C     ***********************************************************************
C     PERM = 4*PI (GM-CM/ABCOUL2) = 4*PI*10-7 WEBER/AMP/METER
C     ***********************************************************************
C     COND = (SEC-ABCOUL2/GM/CM3 = 10-11 1/OHM/METER
C     ***********************************************************************
C     IRST=(0) NO RESTART, =(-1) WRITE RESTART TAPE,=(1) READ RESTART
C     ***********************************************************************
C     ***** I=INVISCID(BL=0.);L=LAMINAR(BL=1.);T=TURBULENCE(BL=2.) *****
C     **** NO EMF(EMF=0.); M=MAGN INDC(EMF=1.); P=LORENTZ(EMF=2.) ******
C     **** MCALC *****    0    1    2    3    4    5    6    7    8
C                         I    L    T   I,M  L,M  T,M  I,P  L,P  T,P
C     ***********************************************************************
C
C

      BL=0.
      SPINSL=0.
      SPACE=0.
      EMF=0.
      PI=3.1416
      WRITE (6,310)
C     ***********************************************************************
C     ******** INITIALIZING CELL VALUES AND DEFINING MATERIAL **********
C     ***************************** PROPERTIES ****************************
C     ***********************************************************************
      READ (5,160) KMAX,JMAX,IAXI,IPTSF,ISYM(1),ISYM(2),ISYM(3),ISYM(4),
     1NVECT,NPDIM,MCALC,IRST,IOBQ,IPOT
      IF (MCALC.EQ.1.OR.MCALC.EQ.4.OR.MCALC.EQ.7) BL=1.
      IF (MCALC.EQ.2.OR.MCALC.EQ.5.OR.MCALC.EQ.8) BL=2.
      IF (MCALC.GT.2.AND.MCALC.LT.6) EMF=1.
      IF (MCALC.GT.5) EMF=2.
      IBL=1.+BL*3.
      IBH=IBL+2
      IEMFL=1.+EMF*3.
      IEMFH=IEMFL+2
      WRITE (6,140) (BLAYER(I),I=IBL,IBH),(ELECT(J),J=IEMFL,IEMFH)
      IF (IOBQ.EQ.0) GO TO 20
      DO 10 N=1,25
      RD(N)=0.
   10 XD(N)=0.
      IOK=IABS(IOBQ)
      READ (5,170) (RD(I),XD(I),I=1,IOK)
C     IF (NVECT.EQ.2) READ (5,120) (RB(I),XB(I),I=1,IOK)
   20 IF (IPOT.EQ.0) GO TO 30
      READ (5,180) SPACE,SPINSL,BASEP,DPOT,DVOLT,JPLMIN,JPLMAX
   30 READ (5,190) NPRN,KPDEL,JPDEL,NPLOT,NDIGPL,NMAX,NCYCLE
      READ (5,200) DZO,DRO,ZMIN,RMIN,MINDT,MAXDT,STAB,TZERO
      READ (5,210) RHOO,VZ,VR,EO,BO,BRO,BZO,PHIO
      READ (5,220) VISCO,PERMO,MW,ARFV
      TIME=TZERO
      PERMO=PERMO*4.*PI
      KP1=KMAX+1
      JP1=JMAX+1
      KP2=KMAX+2
      JP2=JMAX+2
```

```
      WRITE (6,240) KMAX,JMAX,IAXI,IPTSF,ISYM(1),ISYM(2),ISYM(3),ISYM(4)
     1,NVECT,NPDIM,MCALC,IRST,IOBQ,IPOT
      IF(IOBQ.NE.0) WRITE(6,245) (RD(I),XD(I),I=1,IOK)
      IF (IOBQ.NE.0) WRITE (6,120)
      IF (IPOT.NE.0) WRITE (6,250) SPACE,SPINSL,BASEP,DPOT,DVOLT,JPLMIN,
     1JPLMAX
      WRITE (6,260) NPRN,KPDEL,JPDEL,NPLOT,NDIGPL,NMAX,NCYCLE
      WRITE (6,270) DZO,DRO,ZMIN,RMIN,MINDT,MAXDT,STAB,TZERO
      WRITE (6,280) RHOO,VZ,VR,EO,BO,BRO,BZO,PHIO
      WRITE (6,290) VISCO,PERMO,MW,ARFV
      DO 40 J=1,JP2
      IOBL(J)=KP2+1
      IOBK(J)=KP2+1
      IGRAPH(J)=KP2+1
      DANGLE(J)=0.
      INSJ(J)=0
      DO 40 K=1,KP2
      RHO(K,J)=RHOO
      U(K,J)=VZ
      V(K,J)=VR
      E(K,J)=EO
      IF(EMF.EQ.2.) PHI(K,J)=PHIO
      IF (EMF.NE.1.) GO TO 40
      BO(K,J)=BO
      BR(K,J)=BRO
      BZ(K,J)=BZO
   40 CONTINUE
      PERM=PERMO
      VISC=VISCO
C     ***********************************************************************
C     ***************** ASSIGNING VALUES TO SPECIAL CELLS ******************
C     ***********************************************************************
   50 READ (5,230) K1,J1,K2,J2,BRHOO,BVZ,BVR,BEO,BBO,BBRO,BBZO,BPHIO,BVI
     1SCO,BPERMO
      IF (K1.EQ.0) GO TO 80
      BPERMO=BPERMO*4.*PI
      WRITE (6,300) K1,J1,K2,J2,BRHOO,BVZ,BVR,BEO,BBO,BBRO,BBZO,BPHIO,BV
     1ISCO,BPERMO
      DO 70 K=K1,K2
      DO 70 J=J1,J2
      RHO(K,J)=BRHOO
      V(K,J)=BVR
      U(K,J)=BVZ
      E(K,J)=BEO
      IF (EMF.NE.1.) GO TO 60
      BO(K,J)=BBO
      BR(K,J)=BBRO
      BZ(K,J)=BBZO
   60 CONTINUE
      IF(EMF.EQ.2.) PHI(K,J)=BPHIO
      VISC=BVISCO
      PERM=BPERMO
   70 CONTINUE
      GO TO 50
   80 CONTINUE
      WRITE (6,310)
      WRITE (6,130)
      IF (IRST.LT.1) GO TO 110
C     ***********************************************************************
C     ********************* READ INPUT TAPE FOR RESTART *********************
C     ***********************************************************************
      REWIND 15
      READ (15) IRST,NCYCLE,T,DT
      NMAX=NCYCLE+NMAX
```

```
      TIME=T                                                                  384
      WRITE (6,150) IRST,NCYCLE,TIME                                          385
      DO 100 IZ=1,JP2                                                         386
      DO 100 IX=1,KP2                                                         387
      IF (EMF.NE.1.) GO TO 90                                                 388
      BFT=BO(IX,IZ)                                                           389
      BFR=BR(IX,IZ)                                                           390
      BFZ=BZ(IX,IZ)                                                           391
   90 CONTINUE                                                                392
      IF(EMF.EQ.2.) BPHI=PHI(IX,IZ)                                           393
      READ(15) RHO(IX,IZ),U(IX,IZ),V(IX,IZ),E(IX,IZ),BFT,BFR,BFZ,BPHI        394
  100 CONTINUE                                                                395
  110 CONTINUE                                                                396
      CALL GEOM                                                               397
      RETURN                                                                  398
C                                                                             399
C                                                                             400
C                                                                             401
  120 FORMAT (//)                                                             402
  130 FORMAT(1H1)                                                             403
  140 FORMAT (//,20X,3A4,5X,3A4,//)                                           404
  150 FORMAT (1X,120(1HX),/,25X,14HRESTART TAPE  ,I3,2X,10HFOR CYCLE ,I5      405
     1,2X,8HAT TIME ,E12.4,4H SEC,/,1X,120(1HX))                              406
  160 FORMAT (16I5)                                                           407
  170 FORMAT (8E10.4)                                                         408
  180 FORMAT (5E10.4,2I5)                                                     409
  190 FORMAT (8I5)                                                            410
  200 FORMAT (8E10.4)                                                         411
  210 FORMAT (8E10.4)                                                         412
  220 FORMAT (8E10.4)                                                         413
  230 FORMAT (4I5,/,8E10.4,/,8E10.4)                                          414
  240 FORMAT (9H   KMAX  ,9H   JMAX  ,9H   IAXI  ,9H  IPTSF  ,9H ISYM(1)     415
     1 ,9H ISYM(2) ,9H ISYM(3) ,9H ISYM(4) ,9H NVECT  ,9H  NPDIM  ,9H        416
     2MCALC  ,9H    IRST ,9H   IOBQ  ,9H   IPOT  ,/,14(3X,I3,3X),//)         417
  245 FORMAT(2X,4(11H     RO    ,11H     XO    ),/,2X,8(1X,F10.2),/)        418
  250 FORMAT (2X,10H  SPACE  ,2X,10H  SPINSL  ,2X,10H  BASEP  ,2X,10H        419
     1  DPOT  ,2X,10H  DVOLT  ,2X,6HJPLMIN,2X,6HJPLMAX,/,5(2X,E10.4),2       420
     2(2X,16),//)                                                             421
  260 FORMAT (10H   NPRN  ,10H  KPDEL  ,10H  JPDEL  ,10H  NPLOT  ,10         422
     1H  NDIGPL  ,10H  NMAX  ,10H  NCYCLE  ,/,2X,I5,6X,I5,5(4X,I5),//)        423
  270 FORMAT (2X,10H   DZO   ,2X,10H   DRO   ,2X,10H   ZMIN  ,2X,10H         424
     1  RMIN  ,2X,10H  MINDT  ,2X,10H  MAXDT  ,2X,10H  STAB  ,2X,10          425
     2H  TZERO  ,/,8(1X,E11.4),//)                                            426
  280 FORMAT (2X,10H  RHOO  ,2X,10H   VZ   ,2X,10H   VR   ,2X,10H            427
     1  EO   ,2X,10H   BO   ,2X,10H   BR   ,2X,10H   BZ   ,2X,10             428
     2H   PHI   ,/,8(1X,E11.4),//)                                            429
  290 FORMAT (2X,10H  VISCO  ,2X,10H  PERMO  ,2X,10H   MW   ,2X,10H           430
     1  ARFV  ,/,4(1X,E11.4),//)                                             431
  300 FORMAT (3X,20H  K1   J1   K2   J2 ,/,3X,4I5,/,10H  RHOO  ,10H          432
     1 VZ   ,10H   VR   ,10H   EO   ,10H   BO   ,10H  BRO   ,10              433
     2H   BZO   ,10H  PHIO  ,/,1X,8E10.3,/,10H  VISCO  ,10H  PERMO          434
     3 ,/,1X,2E10.3,//)                                                       435
  310 FORMAT (//,128(1H*),/,128(1H*),/,128(1H*))                              436
      END                                                                     437
      SUBROUTINE OUTPUT                                                       438
C                                                                             439
C                                                                             440
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   441
C     PRINTS OUTPUT FOR HYDRODYNAMIC, MAGNETIC, ELECTRIC  AND VISCOUS         442
C     PARAMETERS                                                              443
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   444
C                                                                             445
C                                                                             446
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,       447
```

```
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                  448
      COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH         449
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                              450
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ     451
      COMMON /GRAVTY/ GC,GR,GZ                                              452
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX               453
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XO(45),ZMIN,RMIN,D    454
     1ZO,DRO,IGRAPH(225),NBOUND                                             455
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IOFN,IPTSF               456
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM    457
     1,NVECT,NPDIM                                                          458
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX     459
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225    460
     1),DIAG(225),SUP(225),CONST(225)                                       461
      COMMON/CSTRSS/TRRA(225),TZZA(225),TOOA(225),TRZA(225),VISC,VISCO      462
      COMMON /CTAPE/ IRST                                                   463
      DIMENSION CON(52)                                                     464
      REAL*8 R,RD,RR                                                        465
      REAL JR,JZ,JR1,JZ1,INT,MINDT,MAXDT                                    466
      DATA BFT,BFR,BFZ,BPHI/0.,0.,0.,0./                                    467
C                                                                           468
C                                                                           469
      POTN=0.                                                               470
      DO 10 KK=1,KP2                                                        471
   10 CON(KK)=0.                                                            472
      ATM=1.013*10.**6                                                      473
      WRITE (6,170)                                                         474
      WRITE (6,160) (TITLE(I),I=1,15)                                       475
C     ************************************************************        476
C     ********** PRINTING HYDRODYNAMIC VARIABLES **********                477
C     ************************************************************        478
      DO 20 J=1,JP2,JPDEL                                                   479
      WRITE (6,150) Z(J),TIME,DT                                            480
      WRITE (6,220)                                                         481
      WRITE (6,190)                                                         482
      WRITE (6,220)                                                         483
      DO 20 L=1,KP2,KPDEL                                                   484
      I=KP2+1-L                                                             485
      RR=R(I)                                                               486
      IF (IAXI.EQ.0) RR=R(I)-10.**5                                         487
      INT=E(I,J)-0.5*(U(I,J)**2+V(I,J)**2)                                  488
      GAMMA=GAMM(I,J)                                                       489
      P=(GAMMA-1.)*RHO(I,J)*INT                                             490
      ZZ=Z(J)                                                               491
      CMACH=0.                                                              492
      CMACH=SQRT(GAMMA*ABS(P)/RHO(I,J))                                     493
      IF (CMACH.NE.0.) CMACH=(U(I,J)**2+V(I,J)**2)**0.5/CMACH               494
      TEMP=(E(I,J)-0.5*(U(I,J)**2+V(I,J)**2))/CV(I,J,0,0)                   495
      P=P/(1.013*10.**6)                                                    496
      WRITE (6,180) J,I,RR,RHO(I,J),U(I,J),V(I,J),E(I,J),INT,P,TEMP,CMAC    497
     1H                                                                     498
   20 CONTINUE                                                              499
      IF (BL.EQ.0..AND.EMF.NE.1) GO TO 70                                   500
C     ************************************************************        501
C     ********** PRINTING VISCOUS-MAGNETO (STRESS) VARIABLES **********    502
C     ************************************************************        503
      WRITE (6,170)                                                         504
      DO 60 J=1,JP2,JPDEL                                                   505
      WRITE (6,150) Z(J),TIME,DT                                            506
      WRITE (6,220)                                                         507
      WRITE (6,200)                                                         508
      WRITE (6,220)                                                         509
      DO 60 L=1,KP2,KPDEL                                                   510
      I=KP2+1-L                                                             511
```

```
      RR=R(I)                                                                512
      IF (IAXI.EQ.0) RR=R(I)-100000.                                         513
      TZZIJ=0.                                                               514
      TRRIJ=0.                                                               515
      TOOIJ=0.                                                               516
      TRZIJ=0.                                                               517
      IF (I.EQ.KP2.OR.J.EQ.JP2) GO TO 40                                     518
      IF (BL.EQ.2) GO TO 30                                                  519
      ERRIPH=(V(I+1,J)-V(I,J))/(R(I+1)-R(I))                                 520
      EZZJPH=(U(I,J+1)-U(I,J))/(Z(J+1)-Z(J))                                 521
      EOOIPH=(V(I+1,J)+V(I,J))/(R(I+1)+R(I))                                 522
      ERZIPH=(U(I+1,J)-U(I,J))/(R(I+1)-R(I))                                 523
      ERZJPH=(V(I,J+1)-V(I,J))/(Z(J+1)-Z(J))                                 524
      EEIJPH=EZZJPH+ERRIPH+EOOIPH                                            525
      TRRIJ=(-2.*VISC*ERRIPH-2./3.*VISC*EEIJPH-BR(I,J)**2/PERM)/ATM          526
      TZZIJ=(-2.*VISC*EZZJPH-2./3.*VISC*EEIJPH-BZ(I,J)**2/PERM)/ATM          527
      TOOIJ=(-2.*VISC*EOOIPH-2./3.*VISC*EEIJPH-BO(I,J)**2/PERM)/ATM          528
      TRZIJ=(VISC*(ERZIPH+ERZJPH)-BR(I,J)*BZ(I,J)/PERM)/ATM                  529
   30 IF (BL.EQ.1) GO TO 40                                                  530
      ERZPH=(U(I+1,J)-U(I,J))/(R(I+1)-R(I))                                  531
      TRZIJ=-EDDY(I,J)*ERZPH                                                 532
   40 CONTINUE                                                               533
      EDMU=EDDY(I,J)+VISC                                                    534
      IF (EMF.NE.1.) GO TO 50                                                535
      BFO=BO(I,J)                                                            536
      BFR=BR(I,J)                                                            537
      BFZ=BZ(I,J)                                                            538
   50 CONTINUE                                                               539
      WRITE (6,180) J,I,RR,BFO,BFR,BFZ,EDMU,TZZIJ,TRRIJ,TOOIJ,TRZIJ         540
     1,TRZIJ                                                                 541
   60 CONTINUE                                                               542
   70 CONTINUE                                                               543
      IF (EMF.LT.2.) GO TO 100                                               544
C     ************************************************************************545
C     ********** PRINTING ELECTRICAL VARIABLES ***********************       546
C     ************************************************************************547
      WRITE (6,170)                                                          548
      DO 90 J=1,JP2,JPDEL                                                    549
      WRITE (6,220)                                                          550
      WRITE (6,210)                                                          551
      WRITE (6,220)                                                          552
      DO 90 L=1,KP2,KPDEL                                                    553
      I=KP2+1-L                                                              554
      RR=R(I)                                                                555
      IF (IAXI.EQ.0) RR=R(I)-100000.                                         556
      JR=0                                                                   557
      JZ=0                                                                   558
      IF (I.EQ.1.OR.I.EQ.KP2.OR.J.EQ.1.OR.J.EQ.JP2) GO TO 80                 559
      IF (J.EQ.2) POTN=0.                                                    560
      UU=U(I,J)                                                              561
      VV=V(I,J)                                                              562
      CALL CURRNT (JZ,JR,EZ,ER,UU,VV,I,J,0,0)                                563
      UU=U(I,J-1)                                                            564
      VV=V(I,J-1)                                                            565
      JM=J-1                                                                 566
      CALL CURRNT (JZ1,JR1,EZ1,ER1,UU,VV,I,JM,0,0)                           567
      CON(I)=POTN                                                            568
      POTN=CON(I)-(JR+JR1)/2.*(Z(J)-Z(J-1))                                  569
      IF (IPTSF.EQ.1) POTN=CON(I)-(EZ+EZ1)/2.*(Z(J)-Z(J-1))                  570
      PVOLT=PHI(I,J)*10.**(-8)                                               571
      IF (IPTSF.NE.2) PVOLT=POTN*10.**(-8)                                   572
      PSI=PHI(I,J)                                                           573
      IF (IPTSF.EQ.2) PSI=POTN                                               574
   80 CONTINUE                                                               575
```

```
      SIGG=SIG(I,J,0,0,0)                                                    576
      BETT=BETA(I,J,0,0)                                                     577
      RGAG=RGAS(P,T)                                                         578
      T=(E(I,J)-0.5*(U(I,J)**2+V(I,J)**2))/CV(I,J,0,0)                       579
      BB=B(I,J)                                                              580
      WRITE (6,180) J,I,PVOLT,PSI,BB,BETT,SIGG,JZ,JR,EZ,ER                   581
   90 CONTINUE                                                               582
  100 CONTINUE                                                               583
      IF (NDIGPL.NE.0) CALL DIGPLT                                           584
C     ************************************************************************585
C     ************************** RESTART TAPE ********************************586
C     ************************************************************************587
      IF (MOD(NCYCLE,NPRN).NE.0) GO TO 130                                   588
      IF (IRST.EQ.0) GO TO 130                                               589
      REWIND 15                                                              590
      WRITE (6,140) IRST,NCYCLE,TIME                                         591
      TZERO=TIME                                                             592
      IRST=IRST+1                                                            593
      IF (IRST.EQ.0) IRST=1                                                  594
      LMAX=NMAX+NPRN                                                         595
      WRITE (15) IRST,NCYCLE,TIME,DT                                         596
      DO 120 IZ=1,JP2                                                        597
      DO 120 IX=1,KP2                                                        598
      IF(EMF.EQ.2.) PHI(IX,IZ)=BPHI                                          599
      IF(EMF.NE.1.) GO TO 110                                                600
      BO(IX,IZ)=BFT                                                          601
      BR(IX,IZ)=BFR                                                          602
      BZ(IX,IZ)=BFZ                                                          603
  110 CONTINUE                                                               604
  120 CONTINUE                                                               605
  130 CONTINUE                                                               606
      RETURN                                                                 607
C                                                                            608
C                                                                            609
C                                                                            610
  140 FORMAT (1X,120(1HX),/,25X,14HRESTART TAPE  ,I3,2X,10HFOR CYCLE ,I5     611
     1,2X,8HAT TIME ,E12.4,4H SEC,/,1X,120(1HX))                             612
  150 FORMAT (/,25X,5HZ =  ,E12.4,5X,7HTIME = ,E12.4,5X,5HDT = ,E12.4,/)     613
  160 FORMAT (25X,15A4,/)                                                    614
  170 FORMAT (1H1)                                                           615
  180 FORMAT (2(2X,I3),9(1X,E12.5))                                          616
  190 FORMAT (2X,3H J ,2X,3H I ,13H      R      ,13H  DENSITY   ,13H        617
     1VELOC-Z   ,13H   VELOC-R   ,13H TOT ENERGY  ,13H INT ENERGY  ,13H     618
     2 PRESSURE   ,13H TEMPERATURE ,13H   MACH NO   ,/,10X,13H     CM       619
     3   ,13H   GM/CM3    ,13H   CM/SEC    ,13H   CM/SEC    ,13H   ERG/G    620
     4M    ,13H   ERG/GM    ,13H ATMOSPHERES ,13H  DEGREE K   ,13H     -     621
     5--     ,//)                                                           622
  200 FORMAT (2X,3H J ,2X,3H I ,13H      R      ,13H      B      ,13H        623
     1  BR      ,13H     BZ      ,13H  EDDY+VISC  ,13H     TZZ     ,13H     624
     2    TRR     ,13H     TOO     ,13H     TRZ     ,/,10X,13H      CM      625
     3   ,13H    GAUSS    ,13H    GAUSS    ,13H    GAUSS    ,13H  GM/CM-     626
     4SEC  ,13H     ATM     ,13H     ATM     ,13H     ATM     ,13H     A      627
     5TM     ,//)                                                           628
  210 FORMAT (2X,3H J ,2X,3H I ,13H  POTENTIAL  ,13H STREAM FNCT ,13H        629
     1   B      ,13H     BETA    ,13H ELECT COND  ,13H      JZ     ,13H      630
     2     JR     ,13H     EZ      ,13H     ER      ,/,10X,13H  VOLTS*E8     631
     3   ,13H   AMP/CM38  ,13H  GAUSS      ,13H             ,13H MHO/M E    632
     411   ,13H  AMP/CM2    ,13H  AMP/CM2    ,13H GAUSSCM/SEC ,13HGAUSS       633
     5CM/SEC )                                                               634
  220 FORMAT (2X,124(1H*))                                                   635
      END                                                                    636
      SUBROUTINE GRAPH                                                       637
C                                                                            638
C                                                                            639
```

```
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C     WRITES TO DISK VALUES  OF ALL VARIABLES FOR ALL CELLS INORDER
C     FOR PLOTTING LATER
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ
      COMMON /GRAVTY/ GC,GR,GZ
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D
     1ZO,DRO,IGRAPH(225),NBOUND
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF
      COMMON/CSTRSS/TRRA(225),TZZA(225),TOOA(225),TRZA(225),VISC,VISCO
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM
     1,NVECT,NPDIM
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225
     1),DIAG(225),SUP(225),CONST(225)
      DIMENSION DUMVAR(50), DNM(525), CON(52)
      COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTOL,TZERO,T
      REAL*8 R,RD
      REAL  JR,JZ,JR1,JZ1,INT
C
C     ************************************************************************
C     ********** SUBROUTINE RDPLT CONTAINS A VARIABLE LIST **********
C     ************************************************************************
      POTN=0.
      GAMMA=GAMM(1,1)
      LBJ=0
      NUM=KP2*JP2
      RIMH=0.
      DO 110 I=1,KP2
      DO 110 J=1,JP2
      DO 10 L=01,36
   10 DUMVAR(L)=0.
      RIPH=R(I)+DR(I)/2.
      IF (I.EQ.1) GO TO 20
      RIMH=R(I-1)+DR(I)/2.
   20 LBJ=LBJ+1
C     ************************************************************************
C     ********* ASSIGNS VALUES OF CELL (I,J) TO DUMVAR ARRAY **********
C     ************************************************************************
      DUMVAR(1)=I
      DUMVAR(2)=J
      Y=R(I)
      IF (IAXI.EQ.0) Y=R(I)-100000.
      DUMVAR(3)=Y
      DUMVAR(4)=Z(J)
      DUMVAR(5)=DR(I)
      DUMVAR(6)=DZ(J)
      DUMVAR(7)=U(I,J)
      DUMVAR(8)=V(I,J)
      INT=E(I,J)-0.5*(U(I,J)**2+V(I,J)**2)
      DUMVAR(9)=(GAMMA-1.)*RHO(I,J)*INT
      DUMVAR(10)=E(I,J)
      DUMVAR(11)=INT
      DUMVAR(12)=SQRT(GAMMA*ABS(DUMVAR(9))/RHO(I,J))
      IF (DUMVAR(9).NE.0.) DUMVAR(13)=(U(I,J)**2+V(I,J)**2)**0.5/SQRT(GA
     1MMA*ABS(DUMVAR(9))/RHO(I,J))
      DUMVAR(14)=RHO(I,J)
      DUMVAR(15)=3.1416*RHO(I,J)*(RIPH**2-RIMH**2)*DZ(J)
```

```
      IF (EMF.EQ.1.) DUMVAR(16)=BO(I,J)                                  704
      IF (I.EQ.KP2.OR.J.EQ.JP2) GO TO 40                                 705
      ERRIPH=(V(I+1,J)-V(I,J))/(R(I+1)-R(I))                             706
      EZZJPH=(U(I,J+1)-U(I,J))/(Z(J+1)-Z(J))                             707
      EOOIPH=(V(I+1,J)+V(I,J))/(R(I+1)+R(I))                             708
      ERZIPH=(U(I+1,J)-U(I,J))/(R(I+1)-R(I))                             709
      ERZJPH=(V(I,J+1)-V(I,J))-(Z(J+1)-Z(J))                             710
      EEIJPH=EZZJPH+ERRIPH+EOOIPH                                        711
      TRRIJ=-2.*VISC*ERRIPH-2./3.*EEIJPH                                 712
      TZZIJ=-2.*VISC*EZZJPH-2./3.*EEIJPH                                 713
      TOOIJ=-2.*VISC*EOOIPH-2./3.*EEIJPH                                 714
      TRZIJ=VISC*(ERZIPH+ERZJPH)                                         715
      IF (EMF.NE.1.) GO TO 30                                            716
      TRRIJ=TRRIJ+BR(I,J)**2/PERM                                        717
      TZZIJ=TZZIJ+BZ(I,J)**2/PERM                                        718
      TOOIJ=TOOIJ+BO(I,J)**2/PERM                                        719
      TRZIJ=TRZIJ+BR(I,J)*BZ(I,J)/PERM                                   720
30    CONTINUE                                                           721
      DUMVAR(17)=TRRIJ                                                   722
      DUMVAR(18)=TZZIJ                                                   723
      DUMVAR(19)=TOOIJ                                                   724
      DUMVAR(20)=TRZIJ                                                   725
40    CONTINUE                                                           726
      DUMVAR(21)=TIME                                                    727
      DUMVAR(22)=DT                                                      728
      DUMVAR(23)=VISC                                                    729
      IF (EMF.EQ.1.) DUMVAR(24)=BR(I,J)                                  730
      IF (EMF.EQ.1.) DUMVAR(25)=BZ(I,J)                                  731
      IF (EMF.EQ.0.) GO TO 50                                            732
      JZ=0                                                               733
      JR=0                                                               734
      IF (I.EQ.1.OR.I.EQ.KP2.OR.J.EQ.1.OR.J.EQ.JP2) GO TO 50             735
      IF (J.EQ.2) POTN=0.                                                736
      UU=U(I,J)                                                          737
      VV=V(I,J)                                                          738
      CALL CURRNT (JZ,JR,EZ,ER,UU,VV,I,J,0,0)                            739
      UU=U(I,J-1)                                                        740
      VV=V(I,J-1)                                                        741
      JM=J-1                                                             742
      CALL CURRNT (JZ1,JR1,EZ1,ER1,UU,VV,I,JM,0,0)                       743
      DUMVAR(26)=JR                                                      744
      DUMVAR(27)=JZ                                                      745
      DUMVAR(19)=(JR-BETA(I,J,0,0)*JZ)/SIG(I,J,0,0,0)+U(I,J)*B(I,J)      746
      DUMVAR(20)=(JZ+BETA(I,J,0,0)*JR)/SIG(I,J,0,0,0)-V(I,J)*B(I,J)      747
      CON(I)=POTN                                                        748
      POTN=CON(I)-(JR+JR1)/2.*(Z(J)-Z(J-1))                              749
      IF (IPTSF.EQ.1) POTN=CON(I)-(EZ+EZ1)/2.*(Z(J)-Z(J-1))              750
50    CONTINUE                                                           751
      GAMMA=GAMM(I,J)                                                    752
      DUMVAR(28)=GAMMA                                                   753
      SI=SIG(I,J,0,0,0)                                                  754
      DUMVAR(29)=SI                                                      755
      SIGMA=5.668*10.**(-5)                                              756
      DUMVAR(30)=0.                                                      757
      KOBL=KP2+1-IOBL(J)                                                 758
      IF (I.GE.IOBL(J)) DUMVAR(30)=2.                                    759
      IF (NVECT.EQ.1) GO TO 60                                           760
      IF (I.LE.KOBL) DUMVAR(30)=2.                                       761
60    CONTINUE                                                           762
      CVV=CV(I,J,0,0)                                                    763
      DUMVAR(31)=INT/CVV                                                 764
      IF(EMF.NE.2.) GO TO 65                                             765
      PVOLT=PHI(I,J)*10.**(-8)                                           766
      IF (IPTSF.NE.2) PVOLT=POTN*10.**(-8)                               767
```

```
      PSI=PHI(I,J)                                                          768
      IF (IPTSF.EQ.2) PSI=POTN                                              769
      DUMVAR(32)=PVOLT                                                      770
      DUMVAR(33)=PSI                                                        771
      BET=BETA(I,J,0,0)                                                     772
      DUMVAR(34)=BET                                                        773
      DUMVAR(35)=COND(I,J,0,0)                                              774
   65 CONTINUE                                                              775
      IF (I.GT.1.AND.I.LT.KP2.AND.J.GT.1.AND.J.LT.JP2) DUMVAR(36)=(U(I+1    776
     1,J)-U(I-1,J))/(2.*DR(I))+(V(I,J+1)-V(I,J-1))/(2.*DZ(J))               777
      DUMVAR(9)=DUMVAR(9)/(1.013*10.**6)                                    778
      IF (LBJ.EQ.1) INUMB=0                                                 779
      IND=INUMB*36                                                          780
      DO 70 MIN=1,36                                                        781
      IND=INUMB*36+MIN                                                      782
   70 DNM(IND)=DUMVAR(MIN)                                                  783
      INUMB=INUMB+1                                                         784
      IF (I.EQ.KP2.AND.J.EQ.JP2) INUMB=0                                    785
      IF (INUMB.EQ.14) INUMB=0                                              786
      IF (I.LT.KP2.OR.J.LT.JP2) GO TO 90                                    787
      LM1=IND+1                                                             788
C     ************************************************************************ 789
C     ******** WRITES TO DISK (UNIT 14) BLOCKED DATA OF THE ************** 790
C     ********************** CELL PARAMETER VALUES ********************** 791
C     ************************************************************************ 792
      DO 80 LM=LM1,504                                                      793
   80 DNM(LM)=0.                                                            794
   90 IF (INUMB.GT.0) GO TO 100                                             795
      WRITE (14) (DNM(KX),KX=1,504),TIME,NCYCLE,DT                          796
      T=TIME                                                                797
  100 CONTINUE                                                              798
      IF (I.EQ.KP2.AND.J.EQ.JP2) PRINT 120, TIME,NCYCLE                     799
  110 CONTINUE                                                              800
      RETURN                                                                801
C                                                                           802
C                                                                           803
C                                                                           804
  120 FORMAT (12H  T,NCYCLE  ,2X,E12.4,2X,I5)                               805
      END                                                                   806
      SUBROUTINE DIGPLT                                                     807
C                                                                           808
C                                                                           809
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 810
C     GENERATES DIGITAL PLOTS                                               811
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 812
C                                                                           813
C                                                                           814
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,     815
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                  816
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                              817
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ     818
      COMMON /GRAVTY/ GC,GR,GZ                                              819
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX               820
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D    821
     1ZO,DRO,IGRAPH(225),NBOUND                                             822
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF               823
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM    824
     1,NVECT,NPDIM                                                          825
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX     826
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225    827
     1),DIAG(225),SUP(225),CONST(225)                                       828
      DIMENSION IPLT(132)                                                   829
      REAL*8 R,RD                                                           830
      REAL JR,JZ,JZMIN,JZMAX,JRMIN,JRMAX,INT                               831
```

```
C                                                                       832
C                                                                       833
      ATM=1.013*10.**6                                                  834
      GAMMA=GAMM(1,1)                                                   835
      PAMB=1.0*ATM                                                      836
      RMIN=RHO(1,1)                                                     837
      RMAX=RHO(1,1)                                                     838
      UMIN=U(1,1)                                                       839
      UMAX=U(1,1)                                                       840
      VMIN=V(1,1)                                                       841
      VMAX=V(1,1)                                                       842
      PMIN=E(1,1)*RHO(1,1)*(GAMMA-1.)                                   843
      PMAX=E(1,1)*RHO(1,1)*(GAMMA-1.)                                   844
      CMIN=(U(1,1)**2+V(1,1)**2)**0.5/SQRT(GAMMA*ABS(PMIN)/RHO(1,1))    845
      CMAX=(U(1,1)**2+V(1,1)**2)**0.5/SQRT(GAMMA*ABS(PMIN)/RHO(1,1))    846
      PMIN=E(1,1)*RHO(1,1)*(GAMMA-1.)/ATM                               847
      PMAX=E(1,1)*RHO(1,1)*(GAMMA-1.)/ATM                               848
      TMIN=10.**7                                                       849
      TMAX=-10.**7                                                      850
C     ******************************************************************851
C     ******** SEEKING MINIMUM/MAXIMUM VALUES FOR PRESSURE, ************852
C     ************* VELOCITIES, DENSITY, MAGN INDUCTION ****************853
C     ****************** AND MACH NUMBER ***********************************854
C     ******************************************************************855
      DO 10 K=1,KP2                                                     856
      DO 10 J=1,JP2                                                     857
      INT=E(K,J)-0.5*(U(K,J)**2+V(K,J)**2)                              858
      GAMMA=GAMM(K,J)                                                   859
      P=(GAMMA-1.)*RHO(K,J)*INT                                         860
      IF (RHO(K,J).NE.0.) CMACH=SQRT(GAMMA*ABS(P)/RHO(K,J))             861
      IF (CMACH.NE.0.) CMACH=(U(K,J)**2+V(K,J)**2)**0.5/CMACH           862
      P=P/ATM                                                           863
      RMIN=AMIN1(RMIN,RHO(K,J))                                         864
      RMAX=AMAX1(RMAX,RHO(K,J))                                         865
      UMIN=AMIN1(UMIN,U(K,J))                                           866
      UMAX=AMAX1(UMAX,U(K,J))                                           867
      VMIN=AMIN1(VMIN,V(K,J))                                           868
      VMAX=AMAX1(VMAX,V(K,J))                                           869
      PMIN=AMIN1(PMIN,P)                                                870
      PMAX=AMAX1(PMAX,P)                                                871
      CMIN=AMIN1(CMIN,CMACH)                                            872
      CMAX=AMAX1(CMAX,CMACH)                                            873
      T=INT/CV(K,J,0,0)                                                 874
      TMIN=AMIN1(T,TMIN)                                                875
      TMAX=AMAX1(T,TMAX)                                                876
   10 CONTINUE                                                          877
      DO 50 KJ=1,6                                                      878
      IF (KJ.EQ.1.AND.PMIN.EQ.PMAX) GO TO 50                            879
      IF (KJ.EQ.2.AND.CMIN.EQ.CMAX) GO TO 50                            880
      IF (KJ.EQ.3.AND.RMIN.EQ.RMAX) GO TO 50                            881
      IF (KJ.EQ.4.AND.TMIN.EQ.TMAX) GO TO 50                            882
      IF (KJ.EQ.5.AND.UMIN.EQ.UMAX) GO TO 50                            883
      IF (KJ.EQ.6.AND.VMIN.EQ.VMAX) GO TO 50                            884
      WRITE (6,180)                                                     885
      IF (KJ.EQ.1) WRITE (6,190) PMIN,PMAX                              886
      IF (KJ.EQ.2) WRITE (6,200) CMIN,CMAX                              887
      IF (KJ.EQ.3) WRITE (6,210) RMIN,RMAX                              888
      IF (KJ.EQ.4) WRITE (6,300) TMIN,TMAX                              889
      IF (KJ.EQ.5) WRITE (6,230) UMIN,UMAX                              890
      IF (KJ.EQ.6) WRITE (6,240) VMIN,VMAX                              891
      DO 20 NX=1,125                                                    892
      IPLT(NX)=0                                                        893
   20 IF (NX.GT.105.AND.NX.LT.116) IPLT(NX)=NX-106                      894
      CALL PRTPLT (IPLT,115)                                            895
```

```
      JDIFF=1+JP1/120                                                    896
      DO 40 L=1,KP2,JDIFF                                                897
      K=KP2-L+1                                                          898
      M=0                                                                899
      DO 30 J=1,JP2,JDIFF                                                900
      M=M+1                                                              901
      INT=E(K,J)-0.5*(U(K,J)**2+V(K,J)**2)                               902
      P=(GAMMA-1.)*RHO(K,J)*INT                                          903
      IF (RHO(K,J).NE.0.) CMACH=SQRT(GAMMA*ABS(P)/RHO(K,J))              904
      IF (CMACH.NE.0.) CMACH=(U(K,J)**2+V(K,J)**2)**0.5/CMACH            905
      P=P/ATM                                                            906
      T=INT/CV(K,J,0,0)                                                  907
C     ******************************************************************** 908
C     ************** INTERPOLATING BETWEEN MAX AND MIN ***************** 909
C     ******************************************************************** 910
      IF (KJ.EQ.1) IPLT(M)=(P-PMIN)/(PMAX-PMIN)*9.9                      911
      IF (KJ.EQ.2) IPLT(M)=(CMACH-CMIN)/(CMAX-CMIN)*9.9                  912
      IF (KJ.EQ.3) IPLT(M)=(RHO(K,J)-RMIN)/(RMAX-RMIN)*9.9               913
      IF (KJ.EQ.4) IPLT(M)=(T-TMIN)/(TMAX-TMIN)*9.9                      914
      IF (KJ.EQ.5) IPLT(M)=(U(K,J)-UMIN)/(UMAX-UMIN)*9.9                 915
      IF (KJ.EQ.6) IPLT(M)=(V(K,J)-VMIN)/(VMAX-VMIN)*9.9                 916
      KOBL=KP2+1-IOBL(J)                                                 917
      IF (K.GE.IOBL(J)) IPLT(M)=-1                                       918
      IF (NVECT.EQ.1) GO TO 30                                           919
      IF (K.LE.KOBL) IPLT(M)=-1                                          920
   30 CONTINUE                                                           921
      N=JP2/JDIFF                                                        922
      CALL PRTPLT (IPLT,N)                                               923
   40 CONTINUE                                                           924
   50 CONTINUE                                                           925
      IF(EMF.NE.2.) GO TO 170                                            926
      JZMIN=10.**12                                                      927
      JRMIN=10.**12                                                      928
      JZMAX=-10.**12                                                     929
      JRMAX=-10.**12                                                     930
      PHIMIN=PHI(1,1)                                                    931
      PHIMAX=PHI(1,1)                                                    932
      SIGMIN=+10.**6                                                     933
      SIGMAX=-10.**6                                                     934
      BETMIN=+10.**6                                                     935
      BETMAX=-10.**6                                                     936
      BMIN=10.**7                                                        937
      BMAX=-10.**7                                                       938
C     ******************************************************************** 939
C     ******** SEEKING MINIMUM/MAXIMUM FOR CURRENTS, TEMPERATURE ******** 940
C     ************** HALL PARAMETER, ELECTRIC CONDUCTION AND ************ 941
C     ************** POTENTIAL OR STREAM FUNCTION ********************** 942
C     ******************************************************************** 943
      DO 90 K=1,KP2                                                      944
      DO 90 J=1,JP2                                                      945
      IF (K.EQ.1.OR.K.EQ.KP2.OR.J.EQ.1.OR.J.EQ.JP2) GO TO 80             946
      I=K                                                                947
      IF (IPTSF.NE.2) GO TO 60                                           948
      DPHIDZ=(PHI(K,J+1)-PHI(K,J-1))/(Z(J+1)-Z(J-1))                     949
      DPHIDR=(PHI(K+1,J)-PHI(K-1,J))/(R(K+1)-R(K-1))                     950
      JZ=SIG(I,J,0,0,1)*((-DPHIDZ+V(I,J)*B(I,J))-BETA(I,J,0,0)*(-DPHIDR- 951
     1U(I,J)*B(I,J)))                                                    952
      JR=SIG(I,J,0,0,1)*(BETA(I,J,0,0)*(-DPHIDZ+V(I,J)*B(I,J))+(-DPHIDR- 953
     1U(I,J)*B(I,J)))                                                    954
      GO TO 70                                                           955
   60 JZ=(PHI(I+1,J)-PHI(I-1,J))/(2.*DR(I))                              956
      JR=-(PHI(I,J+1)-PHI(I,J-1))/(2.*DZ(J))                             957
   70 CONTINUE                                                           958
      JZMIN=AMIN1(JZMIN,JZ)                                              959
```

```
      JZMAX=AMAX1(JZMAX,JZ)                                                    960
      JRMIN=AMIN1(JRMIN,JR)                                                    961
      JRMAX=AMAX1(JRMAX,JR)                                                    962
   80 SIGMIN=AMIN1(SIG(K,J,0,0,0),SIGMIN)                                      963
      SIGMAX=AMAX1(SIG(K,J,0,0,0),SIGMAX)                                      964
      BETMIN=AMIN1(BETA(K,J,0,0),BETMIN)                                       965
      BETMAX=AMAX1(BETA(K,J,0,0),BETMAX)                                       966
      IF (EMF.EQ.1.) BP=(BO(K,J)**2/PERM+BR(K,J)**2/PERM+BZ(K,J)**2/PERM       967
     1)/ATM/2.                                                                 968
      IF (EMF.NE.1.) BP=B(K,J)**2/PERM/ATM                                     969
      BMIN=AMIN1(BMIN,BP)                                                      970
      BMAX=AMAX1(BMAX,BP)                                                      971
      PHIMIN=AMIN1(PHIMIN,PHI(K,J))                                            972
      PHIMAX=AMAX1(PHIMAX,PHI(K,J))                                            973
   90 CONTINUE                                                                 974
      DO 160 KJ=7,12                                                           975
      IF (KJ.EQ.7.AND.JZMIN.EQ.JZMAX) GO TO 160                                976
      IF (KJ.EQ.8.AND.JRMIN.EQ.JRMAX) GO TO 160                                977
      IF (KJ.EQ.9.AND.PHIMIN.EQ.PHIMAX) GO TO 160                              978
      IF (KJ.EQ.10.AND.SIGMIN.EQ.SIGMAX) GO TO 160                             979
      IF (KJ.EQ.11.AND.BETMIN.EQ.BETMAX) GO TO 160                             980
      IF (KJ.EQ.12.AND.BMIN.EQ.BMAX) GO TO 160                                 981
      WRITE (6,180)                                                            982
      IF (KJ.EQ.7) WRITE (6,250) JZMIN,JZMAX                                   983
      IF (KJ.EQ.8) WRITE (6,260) JRMIN,JRMAX                                   984
      PVLTMI=PHIMIN                                                            985
      PVLTMA=PHIMAX                                                            986
      IF (IPTSF.EQ.2) PVLTMI=PVLTMI*10.**(-8)                                  987
      IF (IPTSF.EQ.2) PVLTMA=PVLTMA*10.**(-8)                                  988
      IF (KJ.EQ.9) WRITE (6,270) PVLTMI,PVLTMA                                 989
      IF (KJ.EQ.10) WRITE (6,280) SIGMIN,SIGMAX                                990
      IF (KJ.EQ.11) WRITE (6,290) BETMIN,BETMAX                                991
      IF (KJ.EQ.12) WRITE (6,220) BMIN,BMAX                                    992
      DO 100 NX=1,125                                                          993
      IPLT(NX)=0                                                               994
  100 IF (NX.GT.105.AND.NX.LT.116) IPLT(NX)=NX-106                             995
      CALL PRTPLT (IPLT,115)                                                   996
      JDIFF=1+JP1/120                                                          997
      DO 150 L=1,KP2,JDIFF                                                     998
      K=KP2-L+1                                                                999
      M=0                                                                      1000
      DO 140 J=1,JP2,JDIFF                                                     1001
      M=M+1                                                                    1002
      IF (K.EQ.1.OR.K.EQ.KP2.OR.J.EQ.1.OR.J.EQ.JP2) GO TO 130                  1003
      I=K                                                                      1004
      IF (IPTSF.NE.2) GO TO 110                                                1005
      DPHIDZ=(PHI(K,J+1)-PHI(K,J-1))/(Z(J+1)-Z(J-1))                           1006
      DPHIDR=(PHI(K+1,J)-PHI(K-1,J))/(R(K+1)-R(K-1))                           1007
      JZ=SIG(K,J,0,0,1)*((-DPHIDZ+V(K,J)*B(K,J))-BETA(K,J,0,0)*(-DPHIDR-       1008
     1U(K,J)*B(K,J)))                                                          1009
      JR=SIG(K,J,0,0,1)*(BETA(K,J,0,0)*(-DPHIDZ+V(K,J)*B(K,J))+(-DPHIDR-       1010
     1U(K,J)*B(K,J)))                                                          1011
      GO TO 120                                                                1012
  110 JZ=(PHI(I+1,J)-PHI(I-1,J))/(2.*DR(I))                                    1013
      JR=-(PHI(I,J+1)-PHI(I,J-1))/(2.*DZ(J))                                   1014
  120 CONTINUE                                                                 1015
C     ************************************************************           1016
C     ************** INTERPOLATING BETWEEN MAX AND MIN **************          1017
C     ************************************************************           1018
      IF (KJ.EQ.7) IPLT(M)=(JZ-JZMIN)/(JZMAX-JZMIN)*9.9                        1019
      IF (KJ.EQ.8) IPLT(M)=(JR-JRMIN)/(JRMAX-JRMIN)*9.9                        1020
  130 IF (KJ.EQ.9) IPLT(M)=(PHI(K,J)-PHIMIN)/(PHIMAX-PHIMIN)*9.9               1021
      IF (KJ.EQ.10) IPLT(M)=(SIG(K,J,0,0,0)-SIGMIN)/(SIGMAX-SIGMIN)*9.9        1022
      IF (KJ.EQ.11) IPLT(M)=(BETA(K,J,0,0)-BETMIN)/(BETMAX-BETMIN)*9.9         1023
```

```
      IF (EMF.EQ.1.) BP=(BO(K,J)**2/PERM+BR(K,J)**2/PERM+BZ(K,J)**2/PERM
     1)/ATM/2.                                                          1025
      IF (EMF.NE.1.) BP=B(K,J)**2/PERM/ATM                              1026
      IF (KJ.EQ.12) IPLT(M)=(BP-BMIN)/(BMAX-BMIN)*9.9                   1027
      IF (KJ.EQ.9.OR.KJ.EQ.12) GO TO 140                                1028
      IF (K.EQ.1.OR.K.EQ.KP2) GO TO 150                                 1029
      KOBL=KP2+1-IOBL(J)                                                1030
      IF (K.LE.KOBL) IPLT(M)=-1                                         1031
      IF (NVECT.EQ.1) GO TO 140                                         1032
      IF (K.GE.IOBL(J)) IPLT(M)=-1                                      1033
  140 CONTINUE                                                          1034
      N=JP2/JDIFF                                                       1035
      CALL PRTPLT (IPLT,N)                                              1036
  150 CONTINUE                                                          1037
  160 CONTINUE                                                          1038
  170 CONTINUE                                                          1039
      RETURN                                                            1040
C                                                                       1041
C                                                                       1042
C                                                                       1043
  180 FORMAT (/////)                                                    1044
  190 FORMAT (20X,12H PRESSURE    ,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1045
     1,11HATMOSPHERES,//)                                               1046
  200 FORMAT (20X,12H MACH NO     ,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1047
     1,11H    DMLS    ,//)                                            1048
  210 FORMAT (20X,12H DENSITY     ,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1049
     1,11H   GM/CM3   ,//)                                              1050
  220 FORMAT (20X,12H MAGN PRESS ,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1051
     1,11HATMOSPHERES,//)                                               1052
  230 FORMAT (20X,12HAXIAL-VELOC ,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1053
     1,11H  CM/SEC    ,//)                                             1054
  240 FORMAT (20X,12HRADIAL-VELOC,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1055
     1,11H  CM/SEC    ,//)                                             1056
  250 FORMAT (20X,12H CURRENT - Z,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1057
     1,11HABCOUL/SEC ,//)                                               1058
  260 FORMAT (20X,12H CURRENT - R,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1059
     1,11HABCOUL/SEC ,//)                                               1060
  270 FORMAT (20X,12H PHI OR PSI ,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1061
     1,11H           ,//)                                             1062
  280 FORMAT (20X,12HCONDUCTIVITY,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1063
     1,11HMHO/M E11  ,//)                                               1064
  290 FORMAT (20X,12HHALL PARAMTR,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1065
     1,11H    DMLS    ,//)                                            1066
  300 FORMAT (20X,12H TEMPERATURE,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X 1067
     1,11H  DEG K     ,//)                                            1068
      END                                                               1069
      SUBROUTINE PRTPLT (A,N)                                           1070
C                                                                       1071
C                                                                       1072
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1073
C     DIGITAL PRINT (SHADE) ROUTINE                                     1074
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1075
C                                                                       1076
C                                                                       1077
      IMPLICIT INTEGER (A-Z)                                            1078
      DIMENSION A(132), B(132), SPECCH(3)                               1079
      DATA ONE/1H'/,TWO/1H//,THREE/1HX/,FOUR/1HO/,FIVE/1H#/,SIX/1H@/,SEV 1080
     1EN/1H-/,BLANK/1H /,SPECCH/1HM,1HW,1HI/                            1081
      DATA DOT/1H./                                                     1082
C                                                                       1083
C                                                                       1084
      DO 10 I=1,132                                                     1085
   10 B(I)=BLANK                                                        1086
      DO 20 I=1,N                                                       1087
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```
      IF (A(I).EQ.-1) B(I)=DOT                                          1088
      IF (A(I).EQ.1) B(I)=ONE                                           1089
      IF (A(I).EQ.2) B(I)=TWO                                           1090
      IF (A(I).EQ.3) B(I)=THREE                                         1091
      IF (A(I).GE.4) B(I)=FOUR                                          1092
   20 CONTINUE                                                          1093
      WRITE (6,130) B                                                   1094
      DO 30 I=1,132                                                     1095
   30 B(I)=BLANK                                                        1096
      DO 40 I=1,N                                                       1097
      IF (A(I).LT.4) GO TO 40                                           1098
      IF (A(I).EQ.4) B(I)=SEVEN                                         1099
      IF (A(I).EQ.5) B(I)=TWO                                           1100
      IF (A(I).GE.6) B(I)=THREE                                         1101
      FLAG=1                                                            1102
   40 CONTINUE                                                          1103
      IF (FLAG.EQ.0) GO TO 120                                          1104
      WRITE (6,140) B                                                   1105
      FLAG=0                                                            1106
      DO 50 I=1,132                                                     1107
   50 B(I)=BLANK                                                        1108
      DO 60 I=1,N                                                       1109
      IF (A(I).LT.7) GO TO 60                                           1110
      IF (A(I).EQ.7) B(I)=SEVEN                                         1111
      IF (A(I).GE.8) B(I)=FIVE                                          1112
      FLAG=1                                                            1113
   60 CONTINUE                                                          1114
      IF (FLAG.EQ.0) GO TO 120                                          1115
      WRITE (6,140) B                                                   1116
      FLAG=0                                                            1117
      DO 70 I=1,132                                                     1118
   70 B(I)=BLANK                                                        1119
      DO 80 I=1,N                                                       1120
      IF (A(I).LT.8) GO TO 80                                           1121
      IF (A(I).EQ.8) B(I)=THREE                                         1122
      IF (A(I).EQ.9) B(I)=SIX                                           1123
      FLAG=1                                                            1124
   80 CONTINUE                                                          1125
      IF (FLAG.EQ.0) GO TO 120                                          1126
      WRITE (6,140) B                                                   1127
      FLAG=0                                                            1128
      DO 90 I=1,132                                                     1129
   90 B(I)=BLANK                                                        1130
      DO 110 I=1,3                                                      1131
      DO 100 J=1,N                                                      1132
      IF (A(J).NE.9) GO TO 100                                          1133
      B(J)=SPECCH(I)                                                    1134
      FLAG=1                                                            1135
  100 CONTINUE                                                          1136
      IF (FLAG.EQ.0) GO TO 120                                          1137
      WRITE (6,140) B                                                   1138
  110 CONTINUE                                                          1139
  120 RETURN                                                            1140
C                                                                       1141
C                                                                       1142
C                                                                       1143
  130 FORMAT (1H ,132A1)                                                1144
  140 FORMAT (1H+,132A1)                                                1145
      END                                                               1146
      SUBROUTINE GEOM                                                   1147
C                                                                       1148
C                                                                       1149
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  1150
C     SETS UP GRID GEOMETRY BY SPACING CELLS AT INTERVALS OF (DR,DZ)     1151
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```
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   1152
C                                                                                          1153
C                                                                                          1154
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                                             1155
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D                   1156
     1ZO,DRO,IGRAPH(225),NBOUND                                                            1157
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ                    1158
      REAL*8 R,RD                                                                          1159
C                                                                                          1160
C                                                                                          1161
      DZ(1)=DZO                                                                            1162
      DR(1)=DRO                                                                            1163
      Z(1)=ZMIN+DZ(1)/2.                                                                   1164
      R(1)=RMIN+DR(1)/2.                                                                   1165
      IF (IAXI.EQ.0) R(1)=R(1)+100000.                                                     1166
      DO 10 I=2,KP2                                                                        1167
      DR(I)=DRO                                                                            1168
   10 R(I)=R(I-1)+(DR(I)+DR(I-1))/2.                                                       1169
      DO 20 J=2,JP2                                                                        1170
      DZ(J)=DZO                                                                            1171
   20 Z(J)=Z(J-1)+(DZ(J)+DZ(J-1))/2.                                                       1172
      RETURN                                                                               1173
      END                                                                                  1174
      SUBROUTINE BOUND                                                                     1175
C                                                                                          1176
C                                                                                          1177
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   1178
C     BOUNDARY VALUES ASSIGNED AT BOTTOM, LEFT, TOP AND RIGHT FACES                        1179
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   1180
C                                                                                          1181
C                                                                                          1182
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,                    1183
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                                 1184
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                                             1185
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ                    1186
      COMMON /GRAVTY/ GC,GR,GZ                                                             1187
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX                              1188
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D                   1189
     1ZO,DRO,IGRAPH(225),NBOUND                                                            1190
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF                              1191
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM                   1192
     1,NVECT,NPDIM                                                                         1193
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX                    1194
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225                   1195
     1),DIAG(225),SUP(225),CONST(225)                                                      1196
      REAL*8 R,RD,RR,RDIST,ARG                                                             1197
      DATA NO/0/                                                                           1198
C                                                                                          1199
C                                                                                          1200
C     ISYM = 1 (BOTTOM), = 2 (LEFT), = 3 (TOP), = 4 (RIGHT)                                1201
C     IF(ISYM( ) = +1 = TRANSMISSIVE, = -1 = REFLECTIVE                                    1202
C     IF(ISYM( ) = +2 = FIRST DERIVATIVES OF RHO,U,V AND P ARE CONSTANT                    1203
      KP3=KMAX+3                                                                           1204
      JP3=JMAX+3                                                                           1205
C     ***************************************************************                      1206
C                                                                                          1207
      IF (ISYM(1).EQ.0) GO TO 20                                                           1208
      IP=ISYM(1)/IABS(ISYM(1))                                                             1209
      DO 10 J=1,JP2                                                                        1210
      RHO(1,J)=RHO(2,J)+(RHO(2,J)-RHO(3,J))*(IABS(ISYM(1))-1)                              1211
      U(1,J)=+U(2,J)+(U(2,J)-U(3,J))*(IABS(ISYM(1))-1)                                     1212
      V(1,J)=V(2,J)*IP+(V(2,J)-V(3,J))*(IABS(ISYM(1))-1)                                   1213
      E(1,J)=E(2,J)+(E(2,J)-E(3,J))*(IABS(ISYM(1))-1)                                      1214
      E(1,J)=E(1,J)-(U(2,J)**2+V(2,J)**2)/2.+(U(1,J)**2+V(1,J)**2)/2.-((                   1215
```

```
     1U(2,J)**2+V(2,J)**2)/2.-(U(3,J)**2+V(3,J)**2)/2.)*(IABS(ISYM(1))-1      1216
     2)                                                                       1217
C                                                                             1218
      IF (EMF.NE.1.) GO TO 10                                                 1219
      BO(1,J)=BO(2,J)+(B(2,J)-B(3,J))*(IABS(ISYM(1))-1)                       1220
      BR(1,J)=BR(2,J)+(BR(2,J)-BR(3,J))*(IABS(ISYM(1))-1)                     1221
      BZ(1,J)=BZ(2,J)+(BZ(2,J)-BZ(3,J))*(IABS(ISYM(1))-1)                     1222
   10 CONTINUE                                                                1223
C     ************************************************************************1224
   20 IF (ISYM(2).EQ.0) GO TO 40                                              1225
      IP=ISYM(2)/IABS(ISYM(2))                                                1226
      DO 30 K=1,KP2                                                           1227
      RHO(K,1)=RHO(K,2)+(RHO(K,2)-RHO(K,3))*(IABS(ISYM(2))-1)                 1228
      U(K,1)=U(K,2)*IP+(U(K,2)-U(K,3))*(IABS(ISYM(2))-1)                      1229
      V(K,1)=+V(K,2)+(V(K,2)-V(K,3))*(IABS(ISYM(2))-1)                        1230
      E(K,1)=E(K,2)+(E(K,2)-E(K,3))*(IABS(ISYM(2))-1)                         1231
      E(K,1)=E(K,1)-(U(K,2)**2+V(K,2)**2)/2.+(U(K,1)**2+V(K,1)**2)/2.-((      1232
     1U(K,2)**2+V(K,2)**2)/2.-(U(K,3)**2+V(K,3)**2)/2.)*(IABS(ISYM(1))-1      1233
     2)                                                                       1234
C                                                                             1235
      IF (EMF.NE.1.) GO TO 30                                                 1236
      BO(K,1)=BO(K,2)+(BO(K,2)-BO(K,3))*(IABS(ISYM(2))-1)                     1237
      BR(K,1)=BR(K,2)+(BR(K,2)-BR(K,3))*(IABS(ISYM(2))-1)                     1238
      BZ(K,1)=BZ(K,2)+(BZ(K,2)-BZ(K,3))*(IABS(ISYM(2))-1)                     1239
   30 CONTINUE                                                                1240
C     ************************************************************************1241
C                                                                             1242
   40 IF (ISYM(3).EQ.0) GO TO 60                                              1243
      IP=ISYM(3)/IABS(ISYM(3))                                                1244
      DO 50 J=1,JP2                                                           1245
      RHO(KP2,J)=RHO(KP1,J)+(RHO(KP1,J)-RHO(KMAX,J))*(IABS(ISYM(3))-1)        1246
      U(KP2,J)=U(KP1,J)+(U(KP1,J)-U(KMAX,J))*(IABS(ISYM(3))-1)                1247
      V(KP2,J)=V(KP1,J)*IP+(V(KP1,J)-V(KMAX,J))*(IABS(ISYM(3))-1)             1248
      E(KP2,J)=E(KP1,J)+(E(KP1,J)-E(KMAX,J))*(IABS(ISYM(3))-1)                1249
      E(KP2,J)=E(KP2,J)-(U(KP1,J)**2+V(KP1,J)**2)/2.+(U(KP2,J)**2+V(KP2,      1250
     1J)**2)/2.-((U(KP1,J)**2+V(KP1,J)**2)/2.-(U(KMAX,J)**2+V(KMAX,J)**2      1251
     2)/2.)*(IABS(ISYM(1))-1)                                                 1252
C                                                                             1253
      IF (EMF.NE.1.) GO TO 50                                                 1254
      BO(KP2,J)=BO(KP1,J)+(BO(KP1,J)-BO(KMAX,J))*(IABS(ISYM(3))-1)            1255
      BR(KP2,J)=BR(KP1,J)+(BR(KP1,J)-BR(KMAX,J))*(IABS(ISYM(3))-1)            1256
      BZ(KP2,J)=BZ(KP1,J)+(BZ(KP1,J)-BZ(KMAX,J))*(IABS(ISYM(3))-1)            1257
   50 CONTINUE                                                                1258
C     ************************************************************************1259
C                                                                             1260
   60 IF (ISYM(4).EQ.0) GO TO 80                                              1261
      IP=ISYM(4)/IABS(ISYM(4))                                                1262
      DO 70 K=1,KP2                                                           1263
      RHO(K,JP2)=RHO(K,JP1)+(RHO(K,JP1)-RHO(K,JMAX))*(IABS(ISYM(4))-1)        1264
      U(K,JP2)=U(K,JP1)*IP+(U(K,JP1)-U(K,JMAX))*(IABS(ISYM(4))-1)             1265
      V(K,JP2)=V(K,JP1)+(V(K,JP1)-V(K,JMAX))*(IABS(ISYM(4))-1)                1266
      E(K,JP2)=E(K,JP1)+(E(K,JP1)-E(K,JMAX))*(IABS(ISYM(4))-1)                1267
      E(K,JP2)=E(K,JP2)-(U(K,JP1)**2+V(K,JP1)**2)/2.+(U(K,JP2)**2+V(K,JP      1268
     12)**2)/2.-((U(K,JP1)**2+V(K,JP1)**2)/2.-(U(K,JMAX)**2+V(K,JMAX)**2      1269
     2)/2.)*(IABS(ISYM(1))-1)                                                 1270
C                                                                             1271
      IF (EMF.NE.1.) GO TO 70                                                 1272
      BO(K,JP2)=BO(K,JP1)+(BO(K,JP1)-BO(K,JMAX))*(IABS(ISYM(4))-1)            1273
      BR(K,JP2)=BR(K,JP1)+(BR(K,JP1)-BR(K,JMAX))*(IABS(ISYM(4))-1)            1274
      BZ(K,JP2)=BZ(K,JP1)+(BZ(K,JP1)-BZ(K,JMAX))*(IABS(ISYM(4))-1)            1275
   70 CONTINUE                                                                1276
   80 CONTINUE                                                                1277
C                                                                             1278
C     OBLIQUE BOUNDARY CONDITIONS                                             1279
```

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C                                                                       1280
      IF (IOBQ.EQ.0) GO TO 180                                          1281
      JBDRL=1                                                           1282
      JBDRH=JP2                                                         1283
      ND=ND+1                                                           1284
      KT=0                                                              1285
      DO 170 J=JBDRL,JBDRH                                              1286
      IK=IABS(IOBQ)                                                     1287
      IF (Z(J).LT.XD(1).OR.Z(J).GT.XD(IK)) GO TO 170                    1288
      DO 160 MIT=1,NVECT                                                1289
      IW=0                                                              1290
      KM1=KP2/2                                                         1291
      KM2=KM1+1                                                         1292
      IF (NVECT.EQ.1) KM1=KP2                                           1293
      DO 150 N=1,KM1                                                    1294
      IF (MIT.EQ.1) K=N+KM1                                             1295
      IF (MIT.EQ.2) K=KM2-N                                             1296
      IF (NVECT.EQ.1) K=N                                               1297
      I=K-1                                                             1298
      IF (ND-1) 90,90,100                                               1299
   90 CALL OBLQUE (J,RDIST,DELTA)                                       1300
C     ********************************************************************1301
C     RDIST SHOULD BE DOUBLE PRECISION ON IBM MACHINES                  1302
C     ********************************************************************1303
      RR=R(K)                                                           1304
      IF (RDIST-RR) 110,110,140                                         1305
  100 IF (MIT.EQ.1.AND.K.GE.IOBL(J)) GO TO 110                          1306
      IO=KP2+1-IOBL(J)                                                  1307
      IF (MIT.EQ.2.AND.K.LE.IO) GO TO 110                               1308
      GO TO 140                                                         1309
  110 IW=IW+1                                                           1310
      IF (IW.GT.1) GO TO 130                                            1311
      IF (ND.GT.1.AND.MIT.EQ.1) DELTA=DANGLE(J)                         1312
      IF (ND.GT.1.AND.MIT.EQ.2) DELTA=-DANGLE(J)                        1313
      DELTX=DELTA                                                       1314
      L=1                                                               1315
      IF (MIT.EQ.2) L=-1                                                1316
      THETA=0.                                                          1317
      NN=K-L                                                            1318
C     ********************************************************************1319
C     ********************* SETTING V*N CONDITIONS *********************1320
C     ********************************************************************1321
      IF (V(NN,J).NE.0.) THETA=V(NN,J)/ABS(V(NN,J))*2.*3.1416/360.*90.  1322
      IF (U(NN,J).NE.0.) THETA=ATAN(V(NN,J)/U(NN,J))                    1323
      IF (THETA.GT.0..AND.U(NN,J).LT.0.) THETA=THETA+3.1416             1324
      IF (THETA.LT.0..AND.U(NN,J).LT.0.) THETA=THETA+3.1416             1325
      VC=(U(K-L,J)**2+V(K-L,J)**2)**0.5                                 1326
      VX=IOBQ/IABS(IOBQ)*COS(THETA+DELTX)*VC                            1327
      VY=-SIN(THETA+DELTX)*VC                                           1328
      U(K,J)=VY*SIN(DELTX)+VX*COS(DELTX)                                1329
      V(K,J)=VY*COS(DELTX)-VX*SIN(DELTX)                                1330
      RHO(K,J)=RHO(K-L,J)                                               1331
      E(K,J)=E(K-L,J)                                                   1332
      IF (EMF.NE.1.) GO TO 120                                          1333
      BO(K,J)=BO(K-L,J)                                                 1334
      BR(K,J)=BR(K-L,J)                                                 1335
      BZ(K,J)=BZ(K-L,J)                                                 1336
  120 CONTINUE                                                          1337
      IF (ND.EQ.2.AND.IPOT.NE.0) CALL PLATE (J,MIT)                     1338
      IF (ND.GT.1) GO TO 140                                            1339
      JLEFT=JBDRL+1                                                     1340
      JRIGHT=JBDRH-1                                                    1341
      IOBK(J)=K+1                                                       1342
      IOBL(J)=K                                                         1343
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      IGRAPH(J)=K                                                        1344
      DANGLE(J)=DELTA                                                    1345
      GO TO 140                                                          1346
  130 RHO(K,J)=RHOO                                                      1347
      U(K,J)=VZ                                                          1348
      V(K,J)=VR                                                          1349
      E(K,J)=EO                                                          1350
      IF (EMF.NE.1.) GO TO 140                                           1351
      BO(K,J)=BO                                                         1352
      BR(K,J)=BRO                                                        1353
      BZ(K,J)=BZO                                                        1354
  140 CONTINUE                                                           1355
  150 CONTINUE                                                           1356
  160 CONTINUE                                                           1357
  170 CONTINUE                                                           1358
  180 CALL SPEC                                                          1359
      RETURN                                                             1360
      END                                                                1361
      SUBROUTINE OBLQUE (J,RDIST,DELTA)                                  1362
C                                                                        1363
C                                                                        1364
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  1365
C     OBLIQUE BOUNDARY COORDINATES                                       1366
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  1367
C                                                                        1368
C                                                                        1369
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                           1370
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ  1371
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D  1372
      REAL*8 R,RD,RDIST,YDIST                                            1373
      DATA IKT/0/                                                        1374
C                                                                        1375
C                                                                        1376
      IOB=IABS(IOBQ)                                                     1377
      IKT=IKT+1                                                          1378
      IF (IKT.GT.1) GO TO 20                                             1379
      DO 10 JM=1,IOB                                                     1380
   10 RD(JM)=RD(JM)+100000.*(1-IAXI)                                     1381
   20 CONTINUE                                                           1382
      JIP=1                                                              1383
      MMAX=IOB-1                                                         1384
      DO 30 M=2,MMAX                                                     1385
      IF (Z(J).GT.XD(M)) JIP=M                                           1386
   30 CONTINUE                                                           1387
      YDIST=RD(JIP)+(Z(J)-XD(JIP))/(XD(JIP+1)-XD(JIP))*(RD(JIP+1)-RD(JIP  1388
     1))                                                                 1389
      ARG=(RD(JIP+1)-RD(JIP))/(XD(JIP+1)-XD(JIP))                        1390
      DELTX=-ATAN(ARG)                                                   1391
      DELTA=DELTX                                                        1392
      RDIST=YDIST                                                        1393
      RETURN                                                             1394
      END                                                                1395
      SUBROUTINE PLATE (J,MIT)                                           1396
C                                                                        1397
C                                                                        1398
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  1399
C     DEFINES ELECTRODE/INSULATOR PAIRS                                  1400
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  1401
C                                                                        1402
C                                                                        1403
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX  1404
      DATA IKT,KT/0,1/                                                   1405
C                                                                        1406
C                                                                        1407
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      INSJ(J)=-1                                                        1408
      IF (J.LT.JPLMIN.OR.J.GT.JPLMAX) RETURN                            1409
      ISPACE=SPACE+1.                                                   1410
      INSUL=SPACE+SPINSL                                                1411
      IF (MIT.EQ.1) IKT=IKT+1                                           1412
      IF (IKT.EQ.ISPACE.AND.MIT.EQ.1) KT=KT+1                           1413
      IF (IKT.LT.ISPACE) INSJ(J)=KT                                     1414
      IF (IKT.GE.ISPACE) INSJ(J)=-1                                     1415
      IF (IKT.EQ.INSUL.AND.MIT.EQ.2) IKT=0                              1416
      RETURN                                                            1417
      END                                                               1418
      SUBROUTINE BNDPOT (I,J)                                           1419
C                                                                       1420
C                                                                       1421
C     ****************************************************************  1422
C     DEFINES ELECTRICAL BOUNDARY CONDITIONS                            1423
C     ****************************************************************  1424
C                                                                       1425
C                                                                       1426
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 1427
     1225),B0(1,1),BR(1,1),BZ(1,1),DE(1,1)                              1428
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                          1429
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 1430
      COMMON /GRAVTY/ GC,GR,GZ                                          1431
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX           1432
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 1433
     1ZO,DRO,IGRAPH(225),NBOUND                                         1434
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF           1435
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM 1436
     1,NVECT,NPDIM                                                      1437
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX 1438
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225 1439
     1),DIAG(225),SUP(225),CONST(225)                                   1440
      COMMON/ETRODE/ANODE(225),CATHOD(225)                              1441
      REAL*8 R,RD                                                       1442
C                                                                       1443
C                                                                       1444
      BET=10.                                                           1445
      IF (J.EQ.2) INSLND=0                                              1446
      I1=KP2-IOBL(J)+2                                                  1447
      I2=IOBL(J)-1                                                      1448
      K=I-1                                                             1449
      IF (I.EQ.I2) K=I+1                                                1450
      IN=1                                                              1451
      IF (I.EQ.I2) IN=2                                                 1452
      L=INSJ(J)                                                         1453
      M=INSJ(J-1)                                                       1454
      IF (INSJ(J).GT.0) INSLND=INSJ(J)                                  1455
      IF (I.EQ.I1.AND.INSJ(J).EQ.1.AND.INSJ(J-1).LT.0) ANODE(L)=0.      1456
      IF (I.EQ.I2.AND.INSJ(J).EQ.1.AND.INSJ(J-1).LT.0) CATHOD(L)=0.     1457
      IF (I.EQ.I1.AND.INSJ(J).GT.1.AND.INSJ(J-1).LT.0) ANODE(L)=ANODE(L- 1458
     11)                                                                1459
      IF (I.EQ.I2.AND.INSJ(J).GT.1.AND.INSJ(J-1).LT.0) CATHOD(L)=CATHOD( 1460
     1L-1)                                                              1461
      IF (I.EQ.I1.AND.INSJ(J).GT.0) ANODE(L)=ANODE(L)-CUR(I,J)*DZ(J)    1462
      IF (I.EQ.I2.AND.INSJ(J).GT.0) CATHOD(L)=CATHOD(L)-CUR(I,J)*DZ(J)  1463
C     IF(INSJ(J).GT.0)  WRITE(6,1250) INSJ(J),J,I,I1,I2,L,ANODE(L),CATHO 1464
C     1D(L)                                                              1465
      IF (I.EQ.I1.AND.INSJ(J).GT.0) PHI(K,J)=PHI(K+1,J)-BETA(K,J,1,0)*DR 1466
     1(K)/DZ(J)*(PHI(K+1,J+1)-PHI(K+1,J-1))/2.                          1467
      IF (I.EQ.I2.AND.INSJ(J).GT.0) PHI(K,J)=PHI(K-1,J)+BETA(K,J,-1,0)*D 1468
     1R(K)/DZ(J)*(PHI(K-1,J+1)-PHI(K-1,J-1))/2.                         1469
      IF (I.EQ.I1.AND.INSJ(J).GT.0.AND.BET.GT.2.5) PHI(K,J)=(+BETA(K,J,0 1470
     1,0)*DR(K)/DZ(J)*(-4.*PHI(K,J-1)+PHI(K,J-2))-4.*PHI(K+1,J)+PHI(K+2, 1471
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```
     2J))/(3.*(-1.-BETA(K,J,0,0)*DR(K)/DZ(J)))                          1472
      IF (I.EQ.I2.AND.INSJ(J).GT.0.AND.BET.GT.2.5) PHI(K,J)=(-BETA(K,J,0 1473
     1,0)*DR(K)/DZ(J)*(-4.*PHI(K,J+1)+PHI(K,J+2))+4.*PHI(K-1,J)-PHI(K-2, 1474
     2J))/(3.*(1.+BETA(K,J,0,0)*DR(K)/DZ(J)))                           1475
      IF (I.EQ.I1.AND.INSJ(J).EQ.-1.AND.INSLND.EQ.0) PHI(K,J)=0.        1476
      IF (I.EQ.I1.AND.INSJ(J).EQ.-1.AND.INSLND.NE.0) PHI(K,J)=ANODE(INSL 1477
     1ND)                                                               1478
      IF (I.EQ.I2.AND.INSJ(J).EQ.-1.AND.INSLND.EQ.0) PHI(K,J)=0.        1479
      IF (I.EQ.I2.AND.INSJ(J).EQ.-1.AND.INSLND.NE.0) PHI(K,J)=CATHOD(INS 1480
     1LND)                                                              1481
      IF (J.EQ.JP1) PHI(I,JP2)=PHI(I1-1,JP1)                            1482
      IF (I.EQ.I1) PHI(I1-2,J)=2.*PHI(I1-1,J)-PHI(I1,J)                 1483
      IF (I.EQ.I2) PHI(I2+2,J)=2.*PHI(I2+1,J)-PHI(I2,J)                 1484
      RETURN                                                            1485
C                                                                       1486
      END                                                               1487
      SUBROUTINE SPEC                                                   1488
C                                                                       1489
C                                                                       1490
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1491
C     ASSIGNS SPECIAL PARAMETER VALUES EVERY CYCLE                      1492
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1493
C                                                                       1494
C                                                                       1495
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 1496
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                              1497
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                          1498
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 1499
      COMMON /GRAVTY/ GC,GR,GZ                                          1500
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX           1501
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 1502
     1ZO,DRO,IGRAPH(225),NBOUND                                         1503
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF           1504
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM 1505
     1,NVECT,NPDIM                                                      1506
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX 1507
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225 1508
     1),DIAG(225),SUP(225),CONST(225)                                   1509
      COMMON/ETRODE/ANODE(225),CATHOD(225)                              1510
      REAL*8 R,RD                                                       1511
      DATA IKT/0/                                                       1512
C                                                                       1513
C                                                                       1514
      IKT=IKT+1                                                         1515
      IF (IKT.GT.1) GO TO 20                                            1516
      DO 10 J=1,JP2                                                     1517
      ANODE(J)=0.                                                       1518
   10 CATHOD(J)=0.                                                      1519
   20 CONTINUE                                                          1520
      RETURN                                                            1521
      END                                                               1522
      SUBROUTINE TMESTP                                                 1523
C                                                                       1524
C                                                                       1525
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1526
C     COMPUTES TIME INTERVAL BETWEEN CYCLES BASED ON STABILITY CRITERIA 1527
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1528
C                                                                       1529
C                                                                       1530
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 1531
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                              1532
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                          1533
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 1534
      COMMON /GRAVTY/ GC,GR,GZ                                          1535
```

```
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX                1536
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D     1537
     1ZO,DRO,IGRAPH(225),NBOUND                                              1538
      COMMON/CSTRSS/TRRA(225),TZZA(225),TOOA(225),TRZA(225),VISC,VISCO       1539
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF                1540
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM     1541
     1,NVECT,NPOIM                                                           1542
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX      1543
      COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH          1544
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225     1545
     1),DIAG(225),SUP(225),CONST(225)                                        1546
      REAL*8 R,RD                                                            1547
      REAL  INT,MINDT,MAXDT                                                  1548
      DATA DTMIN,DTHRM,DMAGN,DCONVM,DVISCM,DVISCZ,DVISCR,DHTZ,DHTR,DCONV     1549
     1R,DCONVZ/11*1.E6/                                                      1550
      DATA DTZ,DTR,DMGZ,DMGR/4*1.E6/                                         1551
      DATA BT/0./                                                            1552
C                                                                            1553
C                                                                            1554
      GAMMA=GAMM(1,1)                                                        1555
      STABMG=0.4                                                             1556
      DO 10 J=2,JP1                                                          1557
      DO 10 K=2,KP1                                                          1558
      INT=E(K,J)-0.5*(U(K,J)**2+V(K,J)**2)                                   1559
      IF (EMF.EQ.1.) BT=(BO(K,J)**2+BR(K,J)**2+BZ(K,J)**2)/STABMG            1560
      VISC=VIS(K,J,0,0)                                                      1561
      P=(GAMMA-1.)*RHO(K,J)*INT                                              1562
C                                                                            1563
      IF (P.NE.0.OR.BT.NE.0.) DTZ=DZ(J)/(SQRT(BT/(RHO(K,J)*PERM)+ABS(GAM     1564
     1MA*P/RHO(K,J))))                                                       1565
      US=ABS(U(K,J))                                                         1566
      IF (US.GT.0.00001) DCONVZ=DZ(J)/ABS(U(K,J))                            1567
      CND=COND(K,J,0,0)                                                      1568
      IF (CND.NE.0.) DHTZ=DZ(J)**2*RHO(K,J)*CV(K,J,0,0)/(2.*CND)             1569
      DMGZ=DZ(J)**2*PERM*SIG(K,J,0,0,0)/2.                                   1570
      IF (VISC.NE.0.) DVISCZ=0.5*RHO(K,J)*DZ(J)**2/VISC                      1571
C                                                                            1572
      IF (P.NE.0.OR.BT.NE.0.) DTR=DR(K)/(SQRT(BT/(RHO(K,J)*PERM)+ABS(GAM     1573
     1MA*P/RHO(K,J))))                                                       1574
      VS=ABS(V(K,J))                                                         1575
      IF (VS.GT.0.00001) DCONVR=DR(K)/ABS(V(K,J))                            1576
      IF (CND.NE.0.) DHTR=DR(K)**2*RHO(K,J)*CV(K,J,0,0)/(2.*CND)             1577
      DMGR=DR(K)**2*PERM*SIG(K,J,0,0,0)/2.                                   1578
      IF (VISC.NE.0.) DVISCR=0.5*RHO(K,J)*DR(K)**2/VISC                      1579
C                                                                            1580
C     ELECTRIC FIELD       DTEF =RHO(I,J)/(SIG*B(I,J)**2)                    1581
      IF (DTZ.LT.DTMIN) DTMIN=DTZ                                            1582
      IF (DTR.LT.DTMIN) DTMIN=DTR                                            1583
      IF (DCONVZ.LT.DCONVM) DCONVM=DCONVZ                                    1584
      IF (DCONVR.LT.DCONVM) DCONVM=DCONVR                                    1585
      IF (DHTZ.LT.DTHRM) DTHRM=DHTZ                                          1586
      IF (DHTR.LT.DTHRM) DTHRM=DHTR                                          1587
      IF (DMGZ.LT.DMAGN) DMAGN=DMGZ                                          1588
      IF (DMGR.LT.DMAGN) DMAGN=DMGR                                          1589
      IF (DVISCZ.LT.DVISCM) DVISCM=DVISCZ                                    1590
      IF (DVISCR.LT.DVISCM) DVISCM=DVISCR                                    1591
      IF (DCONVM.LT.DTMIN) DTMIN=DCONVM                                      1592
C                                                                            1593
   10 CONTINUE                                                               1594
      DT=DTMIN*STAB                                                          1595
      DMAGN=DMAGN*STABMG                                                     1596
      DTHRM=DTHRM*STAB                                                       1597
      IF (DT.LT.MINDT) DT=MINDT                                              1598
      IF (DT.GT.MAXDT) DT=MAXDT                                              1599
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      NCONV=DCONVM/DT                                                   1600
      NVISC=DVISCM/DT                                                   1601
      IF (MOD(NCYCLE,NPRN).EQ.0) WRITE (6,20) DT,DCONVM,DTHRM,DMAGN,DVIS 1602
     1CM,NCONV,NTHRM,NMAGN,NVISC                                        1603
      RETURN                                                            1604
C                                                                       1605
C                                                                       1606
C                                                                       1607
   20 FORMAT (2X,15HTIME STEP (SEC),2X,12H   HYDRO    ,2X,12H CONVECTION 1608
     1 ,2X,12HTHERMAL COND,2X,12H MAGN DFSN  ,2X,12HVISCOUS DFSN,7H  NCO 1609
     2NV,9H     NTHRM,9H     NMAGN,9H     NVISC,//,19X,5(E12.5,2X),4(I8,1X) 1610
     3,//)                                                              1611
      END                                                               1612
      SUBROUTINE HULLP1                                                 1613
C                                                                       1614
C                                                                       1615
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1616
C     LAGRANGIAN REFERENCE FRAME - CALCULATION OF U,V AND E AT TIME(N+1) 1617
C     BASED ON VALUES OF RHO, U, V, E, PHI AND BO, BR, BZ (OR B) AT     1618
C     TIME (N+1)                                                        1619
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1620
C                                                                       1621
C                                                                       1622
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 1623
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                              1624
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                          1625
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 1626
      COMMON /GRAVTY/ GC,GR,GZ                                          1627
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX           1628
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 1629
     1ZO,DRO,IGRAPH(225),NBOUND                                         1630
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF           1631
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM 1632
     1,NVECT,NPDIM                                                      1633
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX 1634
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225 1635
     1),DIAG(225),SUP(225),CONST(225)                                   1636
      COMMON/CSTORE/RHOF(2,225),UF(2,225),VF(2,225),EF(2,225),MFA(225), 1637
     1UA(225),VA(225),UFA(225),VFA(225),EFA(225),PA(225)                1638
      COMMON/CSTRSS/TRRA(225),TZZA(225),TOOA(225),TRZA(225),VISC,VISCO  1639
      COMMON /CMAGN/BFA(225),BZZA(225),BZFA(225),BF(2,225),BFR(2,225),  1640
     1BFZ(2,225)                                                        1641
      REAL*8 R,RD,RDIFF,RIPH,RIMH,RIP3H                                 1642
      REAL JRIPH,JZIPH,JRJPH,JZJPH,JR1,JZ1,JR2,JZ2,JR,JZ                1643
      REAL MU,LAM,MFA,MIP1,MJP1,M                                       1644
      DATA THRM,DEVU,DEVV,DEVE,IL/0.,0.,0.,0.,0/                        1645
C                                                                       1646
C                                                                       1647
C     ********************************************************************* 1648
C     ***** BL=0. (INVISCID); BL=1. (LAMINAR); BL=2. (TURBULENT) ******* 1649
C     ***** EMF=0. (NO EMF); EMF=1. (MAGN INDC); EMF=2. (LORENTZ) ******* 1650
C     ********************************************************************* 1651
C                                                                       1652
C                                                                       1653
C     ********************************************************************* 1654
C     ************************ PHASE ONE ********************************** 1655
C     ********************************************************************* 1656
      IL=IL+1                                                           1657
      GAMMA=GAMM(1,1)                                                   1658
      ILAM=0                                                            1659
      PI=3.1416                                                         1660
      IPSO=1                                                            1661
      DO 130 I=1,KP1                                                    1662
      IPSO=-IPSO                                                        1663
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      IPS=2                                                                  1664
      IPF=1                                                                  1665
      IF (IPSO.LT.0) IPS=1                                                   1666
      IF (IPSO.LT.0) IPF=2                                                   1667
      DO 130 J=1,JP1                                                         1668
      PM=PERM                                                                1669
      RIPH=R(I)+DR(I)/2.                                                     1670
      IF (I.EQ.1) RIMH=R(1)-DR(1)/2.                                         1671
      IF (I.GT.1) RIMH=R(I-1)+DR(I)/2.                                       1672
      RIP3H=R(I+1)+DR(I+1)/2.                                                1673
      RDIFF=RIPH**2-RIMH**2                                                  1674
C     ************************************************************************1675
C     ************** COMPUTING MASS AND DENSITY AT TIME(N) **************** 1676
C     ************************************************************************1677
      M=RHO(I,J)*PI*(RIPH**2-RIMH**2)*DZ(J)                                  1678
      MIP1=RHO(I+1,J)*PI*(RIP3H**2-RIPH**2)*DZ(J)                            1679
      MJP1=RHO(I,J+1)*PI*(RIPH**2-RIMH**2)*DZ(J+1)                           1680
      RHOIPH=(M+MIP1)/(PI*(RIP3H**2-RIMH**2)*DZ(J))                          1681
      RHOJPH=(M+MJP1)/(PI*(RIPH**2-RIMH**2)*(DZ(J)+DZ(J+1)))                 1682
C     ************************************************************************1683
C     ***** COMPUTING DENSITY AND PRESSURE AT CELL INTERFACE ************** 1684
C     ******************** AT TIME(N+1/2) ********************************** 1685
C     ************************************************************************1686
      RHOIPH=RHOIPH*(1.-DT/(2.*RIPH)*(R(I+1)*V(I+1,J)-R(I)*V(I,J))/(R(I+     1687
     11)-R(I)))                                                              1688
      RHOJPH=RHOJPH*(1.-DT/2.*(U(I,J+1)-U(I,J))/(Z(J+1)-Z(J)))               1689
      P=(GAMMA-1.)*RHO(I,J)*(E(I,J)-0.5*(U(I,J)**2+V(I,J)**2))               1690
      PIP1=(GAMMA-1.)*RHO(I+1,J)*(E(I+1,J)-0.5*(U(I+1,J)**2+V(I+1,J)**2)     1691
     1)                                                                      1692
      PJP1=(GAMMA-1.)*RHO(I,J+1)*(E(I,J+1)-0.5*(U(I,J+1)**2+V(I,J+1)**2)     1693
     1)                                                                      1694
      IF (EMF.NE.1.) GO TO 10                                                1695
C     ************************************************************************1696
C     ********************* MAGNETIC PRESSURE ********************************1697
C     ************************************************************************1698
      BP=BO(I,J)**2+BR(I,J)**2+BZ(I,J)**2                                    1699
      BPIP1=BO(I+1,J)**2+BR(I+1,J)**2+BZ(I+1,J)**2                           1700
      BPJP1=BO(I,J+1)**2+BR(I,J+1)**2+BZ(I,J+1)**2                           1701
      P=P+BP/(2.*PERM)                                                       1702
      PIP1=PIP1+BPIP1/(2.*PERM)                                              1703
      PJP1=PJP1+BPJP1/(2.*PERM)                                              1704
C     ************************************************************************1705
C     *** CALCULATION OF VELOCITIES AT CELL INTERFACE AT TIME(N+1/2) ***      1706
C     ******** BASED ON PRESSURE, GRAVITY AND LORENTZ FORCE *************** 1707
C     ************************************************************************1708
   10 UJPH=(U(I,J)+U(I,J+1))/2.-DT/(2.*RHOJPH)*(PJP1-P)/(Z(J+1)-Z(J))-GZ      1709
     1*DT/2.                                                                 1710
      UIPH=(U(I,J)+U(I+1,J))/2.                                              1711
      VIPH=(V(I+1,J)+V(I,J))/2.-DT/(2.*RHOIPH)*(PIP1-P)/(R(I+1)-R(I))-GR     1712
     1*DT/2.                                                                 1713
      VJPH=(V(I,J)+V(I,J+1))/2.                                              1714
      PIPH=(PIP1+P)/2.*(1.-DT*GAMMA*(R(I+1)*V(I+1,J)-R(I)*V(I,J))/(2.*RI     1715
     1PH*(R(I+1)-R(I))))                                                     1716
      PJPH=(PJP1+P)/2.*(1.-DT*GAMMA*(U(I,J+1)-U(I,J))/(2.*(Z(J+1)-Z(J)))     1717
     1)                                                                      1718
      IF (EMF.NE.2.) GO TO 20                                                1719
C     ************************************************************************1720
C     ******** CALCULATION OF ELECTRIC CURRENTS AT CELL INTERFACE ********   1721
C     ************************** AT TIME(N) ********************************1722
C     ************************************************************************1723
C     IPTSF=1, PHI = CURRENT STREAM FUNCTION; =2, PHI = POTENTIAL            1724
C     IPOT =1, ELECTRICAL TERMS OFF; =1, ELECTRICAL TERMS ON                 1725
C     ************************************************************************1726
      IF (I.EQ.1.OR.J.EQ.1.OR.I.EQ.KP2.OR.J.EQ.JP2) GO TO 20                 1727
```

```
      CALL CURRNT (JZIPH,JR,EZ,ER,UIPH,VIPH,I,J,1,0)                    1728
      CALL CURRNT (JZ,JRIPH,EZ,ER,UIPH,VIPH,I,J,1,0)                    1729
      CALL CURRNT (JZJPH,JR,EZ,ER,UJPH,VJPH,I,J,0,1)                    1730
      CALL CURRNT (JZ,JRJPH,EZ,ER,UJPH,VJPH,I,J,0,1)                    1731
      UJPH=UJPH+DT/(2.*RHOJPH)*JRJPH*(B(I,J)+B(I,J+1))/2.               1732
      VIPH=VIPH+DT/(2.*RHOIPH)*(-JZIPH*(B(I,J)+B(I+1,J))/2.)            1733
      PIPH=PIPH+DT*(GAMMA-1.)*(JRIPH**2+JZIPH**2)/(2.*SIG(I,J,1,0,0))   1734
      PJPH=PJPH+DT*(GAMMA-1.)*(JRJPH**2+JZJPH**2)/(2.*SIG(I,J,0,1,0))   1735
   20 CONTINUE                                                          1736
C     ********************************************************************  1737
C     ********** ARTIFICIAL VISCOSITY (IF NECESSARY) ********************  1738
C     ********************************************************************  1739
      DV=V(I+1,J)-V(I,J)                                                1740
      DU=U(I,J+1)-U(I,J)                                                1741
      IF (DV.LT.0.) PIPH=PIPH-DV*ARFV*(GAMMA*PIPH/RHOIPH)**0.5          1742
      IF (DU.LT.0.) PJPH=PJPH-ARFV*DU*(GAMMA*PJPH/RHOJPH)**0.5          1743
C     ********************************************************************  1744
C     ******* CALCULATION OF MAGNETO STRESS TENSOR AT TIME(N) ***********  1745
C     ********************************************************************  1746
      IF (EMF.NE.1.) GO TO 30                                           1747
      BZP1=(BZ(I+1,J)+BZ(I,J+1)+2.*BZ(I+1,J+1))/4.                      1748
      IF (BL.EQ.1.) ILAM=1                                              1749
      BRP1=(BR(I+1,J)+BR(I,J+1)+2.*BR(I+1,J+1))/4.                      1750
      TRRIP1=-BR(I+1,J)**2/PERM                                         1751
      TOOIP1=-BO(I+1,J)**2/PERM                                         1752
      TRZP1=-BRP1*BZP1/PERM                                             1753
      TZZJP1=-BZ(I,J+1)**2/PERM                                         1754
      BRPH=(BR(I+1,J+1)+BR(I+1,J)+BR(I,J+1)+BR(I,J))/4.                 1755
      BZPH=(BZ(I+1,J+1)+BZ(I+1,J)+BZ(I,J+1)+BZ(I,J))/4.                 1756
      TRZP2=-BRP1*BZP1                                                  1757
      TRR=-BR(I,J)**2/PERM                                              1758
      TOO=-BO(I,J)**2/PERM                                              1759
      TRZ1=-BR(I,J)*BZ(I,J)/PERM                                        1760
      TRZ2=-BR(I,J)*BZ(I,J)/PERM                                        1761
      TZZ=-BZ(I,J)**2/PERM                                              1762
C     ********************************************************************  1763
C     ***** CORRECTION TO PRESSURE DUE TO MAGNETO-STRESS AT *************  1764
C     ************** CELL INTERFACE AT TIME(N+1/2) ***********************  1765
C     ********************************************************************  1766
      DEVP1=(R(I+1)*TRRIP1*V(I+1,J)-R(I)*TRR*V(I,J))/(RIPH*(R(I+1)-R(I))  1767
     1)+(R(I+1)*U(I+1,J)*TRZP1-R(I)*U(I,J)*TRZ1)/(RIPH*(R(I+1)-R(I)))    1768
      DEVP2=(TZZJP1*U(I,J+1)-TZZ*U(I,J))/(Z(J+1)-Z(J))+(TRZP2*V(I,J+1)-T  1769
     1RZ2*V(I,J))/(Z(J+1)-Z(J))                                         1770
      PIPH=PIPH-(GAMMA-1.)*DT/(2.*RHOIPH)*DEVP1                         1771
      PJPH=PJPH-(GAMMA-1.)*DT/(2.*RHOJPH)*DEVP2                         1772
C     ********************************************************************  1773
C     ********* CORRECTION OF VELOCITIES AT CELL INTERFACE AT ***********  1774
C     ************ TIME(N+1/2) DUE TO MAGNETO-STRESS *********************  1775
C     ********************************************************************  1776
      UJPH=UJPH-DT/(2.*RHOJPH)*(TZZJP1-TZZ)/DZ(J+1)                     1777
      VIPH=VIPH-DT/(2.*RHOIPH)*((R(I+1)*TRRIP1-R(I)*TRR)/(RIPH*DR(I+1))-  1778
     1(TOOIP1+TOO)/2./RIPH)                                             1779
      UIPH=UIPH-DT/(2.*RHOIPH)*(R(I+1)*TRZP1-R(I)*TRZ1)/(RIPH*DR(I+1))  1780
      VJPH=VJPH-DT/(2.*RHOJPH)*(TRZP2-TRZ2)/DZ(J+1)                     1781
C     ********************************************************************  1782
C     ******* CALCULATION OF LAMINAR STRESS COMPONENTS AT CELL **********  1783
C     ********************INTERFACE AT TIME(N+1/2) ************************  1784
C     ********************************************************************  1785
   30 IF (BL.NE.1.) GO TO 40                                            1786
      ERRIPH=(V(I+1,J)-V(I,J))/(R(I+1)-R(I))                            1787
      EOOIPH=VIPH/RIPH                                                  1788
      ERZPH=(U(I+1,J)-U(I,J))/(R(I+1)-R(I))                             1789
      EZZJPH=(U(I,J+1)-U(I,J))/(Z(J+1)-Z(J))                            1790
      ERZPH2=(V(I,J+1)-V(I,J))/(Z(J+1)-Z(J))                            1791
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```
      EEIJPH=EZZJPH+ERRIPH+EOOIPH                                          1792
      MU=VIS(I,J,1,0)                                                      1793
      LAM=-2./3.*MU                                                        1794
      TRRIPH=-2.*MU*ERRIPH+LAM*EEIJPH                                      1795
      TOOIPH=-2.*MU*EOOIPH+LAM*EEIJPH                                      1796
      TRZPH=-MU*ERZPH                                                      1797
      MU=VIS(I,J,0,1)                                                      1798
      LAM=-2./3.*MU                                                        1799
      TZZJPH=-2.*MU*EZZJPH+LAM*EEIJPH                                      1800
      TRZPH2=-MU*ERZPH2                                                    1801
C     ***********************************************************************1802
C     ******* CALCULATION OF MAGNETO STRESS COMPONENTS AT CELL *********** 1803
C     ********************INTERFACE AT TIME(N+1/2) ************************ 1804
C     ***********************************************************************1805
   40 IF (EMF.NE.1.) GO TO 50                                              1806
      TRRIPH=-((BR(I+1,J)+BR(I,J))/2.)**2/PERM+ILAM*TRRIPH                 1807
      TOOIPH=-((BO(I+1,J)+BO(I,J))/2.)**2/PERM+ILAM*TOOIPH                 1808
      TZZJPH=-((BZ(I,J+1)+BZ(I,J))/2.)**2/PERM+ILAM*TZZJPH                 1809
      TRZPH=-BRPH*BZPH/PERM+ILAM*TRZPH                                     1810
      TRZPH2=-BRPH*BZPH/PERM+ILAM*TRZPH2                                   1811
   50 IF (BL.NE.2.) GO TO 60                                               1812
C     ***********************************************************************1813
C     ******** CALCULATION OF TURBULENT SHEAR AT CELL INTERFACE ********* 1814
C     ************************ AT TIME(N+1/2) ************************** 1815
C     ***********************************************************************1816
      ERZPH=(U(I+1,J)-U(I,J))/(R(I+1)-R(I))                                1817
      MU=VIS(I,J,1,0)                                                      1818
      TRZPH=-(MU+EDDY(I,J))*ERZPH                                          1819
C                                                                          1820
   60 IF (I.EQ.1.OR.J.EQ.1) GO TO 90                                       1821
      PIMH=PA(J)                                                           1822
      UIMH=UA(J)                                                           1823
      VIMH=VA(J)                                                           1824
C     ***********************************************************************1825
C     ********** PRESSURE INFLUENCE ON U,V AND E AT CELL CENTERS ********* 1826
C     ************************ AT TIME(N+1) ************************** 1827
C     ***********************************************************************1828
      SPHU=-DT*(PJPH-PJMH)/(RHO(I,J)*DZ(J))-DT*GZ                          1829
      SPHV=-DT*(PIPH-PIMH)/(RHO(I,J)*DR(I))-DT*GR                          1830
      CMPR=-DT/RHO(I,J)*((RIPH*PIPH*VIPH-RIMH*PIMH*VIMH)/(R(I)*DR(I))+(P   1831
     1JPH*UJPH-PJMH*UJMH)/DZ(J))                                           1832
      IF (EMF.NE.1..AND.BL.NE.1.) GO TO 70                                 1833
C     ***********************************************************************1834
C     ********** LAMINAR AND/OR MAGNETIC INFLUENCE ON U,V AND E ********* 1835
C     ************ AT CELL CENTERS AT TIME(N+1) ********************** 1836
C     ***********************************************************************1837
      TRRIMH=TRRA(J)                                                       1838
      TOOIMH=TOOA(J)                                                       1839
      DEVU=-DT*((RIPH*TRZPH-RIMH*TRZA(J))/(R(I)*DR(I))+(TZZJPH-TZZJMH)/D   1840
     1Z(J))/RHO(I,J)                                                       1841
      DEVV=-DT*((RIPH*TRRIPH-RIMH*TRRIMH)/(R(I)*DR(I))+(TRZPH2-TRZMH2)/D   1842
     1Z(J)-(TOOIPH+TOOIMH)/(RIPH+RIMH))/RHO(I,J)                           1843
      DEVE=-DT/RHO(I,J)*((RIPH*TRRIPH*VIPH-RIMH*TRRIMH*VIMH)/(R(I)*DR(I)   1844
     1)+(RIPH*TRZPH*UIPH-RIMH*TRZA(J)*UIMH)/(R(I)*DR(I))+(TZZJPH*UJPH-TZ   1845
     2ZJMH*UJMH)/DZ(J)+(TRZPH*VJPH-TRZMH*VJMH)/DZ(J))                      1846
   70 IF (BL.NE.2.) GO TO 80                                               1847
C     ***********************************************************************1848
C     ********** TURBULENT SHEAR INFLUENCE ON U,V AND E AT CELL ********* 1849
C     ********************* CENTERS AT TIME(N+1) ********************** 1850
C     ***********************************************************************1851
      DEVU=-DT*((RIPH*TRZPH-RIMH*TRZA(J))/(R(I)*DR(I)))/RHO(I,J)           1852
      DEVV=0.                                                              1853
      DEVE=-DT/RHO(I,J)*(RIPH*TRZPH*UIPH-RIMH*TRZA(J)*UIMH)/(R(I)*DR(I))   1854
C     ***********************************************************************1855
```

```
C     ********* STORING U, V AND E INCREMENTS AT CELL CENTERS AT *********
C     ************************** TIME(N+1)*********************************
C     ***************************************************************************
   80 UF(IPS,J)=SPHU+DEVU
      VF(IPS,J)=SPHV+DEVV
      EF(IPS,J)=CMPR-DT*(V(I,J)+VF(IPS,J))*GR-DT*(U(I,J)+UF(IPS,J))*GZ+D
     1EVE
      IF (EMF.NE.2) GO TO 90
C     ***************************************************************************
C     **** CALCULATION OF ELECTRICAL INFLUENCE ON U,V AND E AT CELL ****
C     ******************** CENTERS AT TIME(N+1) ************************
C     ***************************************************************************
      IF (I.EQ.1.OR.I.EQ.KP2.OR.J.EQ.1.OR.J.EQ.JP2) GO TO 90
      UU=U(I,J)
      VV=V(I,J)
      CALL CURRNT (JZ1,JR1,EZ,ER,UU,VV,I,J,0,0)
      UP=U(I,J)+U(IPS,J)
      VP=V(I,J)+V(IPS,J)
      CALL CURRNT (JZ2,JR2,EZ,ER,UP,VP,I,J,0,0)
      UF(IPS,J)=UF(IPS,J)+JR1*B(I,J)*DT/RHO(I,J)
      VF(IPS,J)=VF(IPS,J)+(-JZ1*B(I,J))*DT/RHO(I,J)
      EF(IPS,J)=EF(IPS,J)+(JZ2*EZ+JR2*ER)*DT/RHO(I,J)
C     ***************************************************************************
C     **** REVERSING CELL INTERFACE VALUES - RIGHT BOUNDARY VALUE *******
C     **** OF LEFT CELL BECOMES LEFT BOUNDARY VALUE OF RIGHT CELL *******
C     ***************************************************************************
   90 VA(J)=VIPH
      UA(J)=UIPH
      PA(J)=PIPH
      UJMH=UJPH
      VJMH=VJPH
      PJMH=PJPH
      IF (EMF.NE.1..AND.BL.NE.1.) GO TO 100
      TRRA(J)=TRR1PH
      TOOA(J)=TOO1PH
      TRZA(J)=TRZPH
      TRZMH=TRZPH
      TRZMH2=TRZPH2
      TZZJMH=TZZJPH
  100 IF (BL.NE.2.) GO TO 110
      TRZA(J)=TRZPH
C     ***************************************************************************
C     ********** ASSIGNING VALUES OF U,V AND E AT TIME(N+1) ***********
C     ***************************************************************************
  110 IF (J.EQ.1.OR.I.LT.3) GO TO 130
      JH=1
      IF (I.EQ.KP1) JH=2
      DO 120 JL=1,JH
      N=I-2+JL
      L=IPF
      IF (JL.EQ.2) L=IPS
      U(N,J)=U(N,J)+UF(L,J)
      V(N,J)=V(N,J)+VF(L,J)
      IF (ABS(U(N,J)).LT.0.00001) U(N,J)=0.
      IF (ABS(V(N,J)).LT.0.00001) V(N,J)=0.
      E(N,J)=E(N,J)+EF(L,J)
  120 CONTINUE
  130 CONTINUE
      RETURN
C
      END
      SUBROUTINE HULLP2
C
C
```

```
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   1920
C     THE TRANSPORTING OF MASS (RE-ZONING)  AND COMPUTATION OF RHO AT                      1921
C     TIME(N+1) BASED ON VALUES OF RHO,U,V AND E AT TIME(N+1).                             1922
C     CORRECTION OF U,V AND E AT TIME(N+1) FOR THE CONVECTION                              1923
C     OF MOMENTUM AND ENERGY RESULTING FROM THE TRANSPORTING OF MASS                       1924
C     BETWEEN CELLS                                                                        1925
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   1926
C                                                                                          1927
C                                                                                          1928
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,                    1929
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                                 1930
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                                             1931
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ                    1932
      COMMON /GRAVTY/ GC,GR,GZ                                                             1933
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX                              1934
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D                   1935
     1ZO,DRO,IGRAPH(225),NBOUND                                                            1936
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF                              1937
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM                   1938
     1,NVECT,NPDIM                                                                         1939
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX                    1940
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225                   1941
     1),DIAG(225),SUP(225),CONST(225)                                                      1942
      COMMON/CSTORE/RHOF(2,225),UF(2,225),VF(2,225),EF(2,225),MFA(225),                    1943
     1UA(225),VA(225),UFA(225),VFA(225),EFA(225),PA(225)                                   1944
      COMMON/CSTRSS/TRRA(225),TZZA(225),TOOA(225),TRZA(225),VISC,VISCO                     1945
      COMMON /CMAGN/BFA(225),BZZA(225),BZFA(225),BF(2,225),BFR(2,225),                     1946
     1BFZ(2,225)                                                                           1947
      REAL*8 R,RD,RIMH,RIPH,RIPP                                                           1948
      REAL M,MIJ,MFIPH,MFIMH,MFJPH,MFJMH,MFA                                               1949
C                                                                                          1950
C                                                                                          1951
C     ************************************************************                         1952
C     **************  PHASE TWO  *********************************                         1953
C     ************************************************************                         1954
C     ************************************************************                         1955
C     *****  CALCULATION OF MASS, MOMENTUM, ENERGY AND MAGNETIC  *********                 1956
C     ***************************  INDUCTION FLUX  ******************                       1957
C     ************************************************************                         1958
      PI=3.14159                                                                           1959
      DO 10 J=2,JP1                                                                        1960
      VIMH=(V(1,J)+V(2,J))/2.                                                              1961
      IDM=1                                                                                1962
      IF (VIMH.LT.0.) IDM=2                                                                1963
      RHOIMH=RHO(IDM,J)*(1.-DT/(R(1)+DR(1)/2.)*(R(2)*V(2,J)-R(1)*V(1,J))                   1964
     1/(R(2)-R(1)))                                                                        1965
      DRR=DR(1)                                                                            1966
      RIPP=R(1)+DRR/2.                                                                     1967
      MFA(J)=VIMH*RHOIMH*2.*PI*(RIPP+0.5*VIMH*DT)*DZ(J)*DT                                 1968
      UFA(J)=MFA(J)*U(IDM,J)                                                               1969
      VFA(J)=MFA(J)*V(IDM,J)                                                               1970
      EFA(J)=MFA(J)*E(IDM,J)                                                               1971
C                                                                                          1972
      IF (EMF.NE.1) GO TO 10                                                               1973
      BFA(J)=VIMH/(R(2)-R(1))*B(IDM,J)*DT                                                  1974
      BRR=(BR(2,J)+BR(1,J))/2.                                                             1975
      BZZA(J)=(U(2,J)+U(1,J))/2./(R(2)-R(1))*BRR*DT                                        1976
      BZFA(J)=(V(2,J)+V(1,J))/2./(R(2)-R(1))*BZ(IDM,J)*DT                                  1977
   10 CONTINUE                                                                             1978
      IPSO=1                                                                               1979
      DO 60 I=2,KP1                                                                        1980
      IPSO=-IPSO                                                                           1981
      IPS=2                                                                                1982
      IPF=1                                                                                1983
```

```
      IF (IPSO.LT.0) IPS=1                                                    1984
      IF (IPSO.LT.0) IPF=2                                                    1985
      DO 60 J=2,JP1                                                           1986
      RIPH=R(I)+DR(I)/2.                                                      1987
      RIMH=R(I-1)+DR(I)/2.                                                    1988
      UJPH=(U(I,J)+U(I,J+1))/2.                                               1989
      VIPH=(V(I,J)+V(I+1,J))/2.                                               1990
      UIPH=(U(I,J)+U(I+1,J))/2.                                               1991
      VJPH=(V(I,J)+V(I,J+1))/2.                                               1992
      IDP=I                                                                   1993
      JDP=J                                                                   1994
      IF (UJPH.LT.0.) JDP=J+1                                                 1995
      IF (VIPH.LT.0.) IDP=I+1                                                 1996
C                                                                             1997
      RHOIPH=RHO(IDP,J)*(1.-DT/RIPH*(R(I+1)*V(I+1,J)-R(I)*V(I,J))/(R(I+1      1998
     1)-R(I)))                                                                1999
      RHOJPH=RHO(I,JDP)*(1.-DT*(U(I,J+1)-U(I,J))/(Z(J+1)-Z(J)))               2000
      MFJPH=UJPH*RHOJPH*2.*PI*R(I)*DR(I)*DT                                   2001
C                                                                             2002
      MFIPH=VIPH*RHOIPH*2.*PI*(RIPH+0.5*VIPH*DT)*DZ(J)*DT                     2003
      IF (J.NE.2) GO TO 20                                                    2004
      UJMH=(U(I,J)+U(I,J-1))/2.                                               2005
      JDM=1                                                                   2006
      IF (UJMH.LT.0.) JDM=2                                                   2007
      RHOJMH=RHO(I,JDM)*(1.-DT*(U(I,J)-U(I,J-1))/(Z(J)-Z(J-1)))               2008
      MFJMH=(U(I,1)+U(I,2))/2.*RHOJMH*2.*PI*R(I)*DR(I)*DT                     2009
      UFJMH=MFJMH*U(I,JDM)                                                    2010
      VFJMH=MFJMH*V(I,JDM)                                                    2011
      EFJMH=MFJMH*E(I,JDM)                                                    2012
C                                                                             2013
      IF (EMF.NE.1) GO TO 30                                                  2014
      BFJMH=UJMH/(Z(J)-Z(J-1))*BO(I,JDM)*DT                                   2015
      BRFJMH=UJMH/(Z(J)-Z(J-1))*BR(I,JDM)*DT                                  2016
      BZZ=(BZ(I,2)+BZ(I,1))/2.                                                2017
      BRIJMH=(V(I,2)+V(I,1))/2./(Z(2)-Z(1))*BZZ*DT                            2018
   20 IF (EMF.NE.1) GO TO 30                                                  2019
      BFIPH=VIPH/(R(I+1)-R(I))*BO(IDP,J)*DT                                   2020
      BZZ=(BZ(I,J)+BZ(I,J+1))/2.                                              2021
      BRIJPH=VJPH/(Z(J+1)-Z(J))*BZZ*DT                                        2022
      BZFIPH=VIPH/(R(I+1)-R(I))*BZ(IDP,J)*DT                                  2023
      BFJPH=UJPH/(Z(J+1)-Z(J))*B(I,JDP)*DT                                    2024
      BRFJPH=UJPH/(Z(J+1)-Z(J))*BR(I,JDP)*DT                                  2025
      BRR=(BR(I,J)+BR(I+1,J))/2.                                              2026
      BZIJPH=UIPH/(R(I+1)-R(I))*BRR*DT                                        2027
   30 CONTINUE                                                                2028
C                                                                             2029
      UFIPH=MFIPH*U(IDP,J)                                                    2030
      VFIPH=MFIPH*V(IDP,J)                                                    2031
      UFJPH=MFJPH*U(I,JDP)                                                    2032
      VFJPH=MFJPH*V(I,JDP)                                                    2033
      EFIPH=MFIPH*E(IDP,J)                                                    2034
      EFJPH=MFJPH*E(I,JDP)                                                    2035
      MFIMH=MFA(J)                                                            2036
      UFIMH=UFA(J)                                                            2037
      VFIMH=VFA(J)                                                            2038
      EFIMH=EFA(J)                                                            2039
C                                                                             2040
C     ************************************************************            2041
C     ************ CALCULATION OF DENSITY AT TIME(N+1) BASED ON *********     2042
C     ********************* MASS FLUX CONTRIBUTIONS *********************     2043
C     ************************************************************            2044
      M=RHO(I,J)*PI*(RIPH**2-RIMH**2)*DZ(J)                                   2045
      MIJ=RHO(I,J)*PI*(RIPH**2-RIMH**2)*DZ(J)+MFIMH+MFJMH-MFIPH-MFJPH         2046
C                                                                             2047
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```
      RHOF(IPS,J)=MIJ/(PI*(RIPH**2-RIMH**2)*DZ(J))                          2048
C                                                                           2049
C     ********************************************************************  2050
C     ************** CORRECTION OF VELOCITIES AND ENERGY DUE **************  2051
C     ************************ CONVECTION ********************************  2052
C     ********************************************************************  2053
      UF(IPS,J)=(U(I,J)*M+UFIMH+UFJMH-UFIPH-UFJPH)/MIJ                      2054
      VF(IPS,J)=(V(I,J)*M+VFIMH+VFJMH-VFJPH-VFIPH)/MIJ                      2055
      INT=(E(I,J)*M+EFIMH+EFJMH-EFIPH-EFJPH-0.5*(U(I,J)**2+V(I,J)**2)*MI    2056
     1J)/MIJ                                                                2057
      EF(IPS,J)=INT+(U(I,J)**2+V(I,J)**2)/2.                                2058
      MFJMH=MFJPH                                                           2059
      UFJMH=UFJPH                                                           2060
      VFJMH=VFJPH                                                           2061
      EFJMH=EFJPH                                                           2062
C                                                                           2063
      IF (EMF.NE.1) GO TO 40                                                2064
      BFIMH=BFA(J)                                                          2065
      BZIJMH=BZZA(J)                                                        2066
      BZFIMH=BZFA(J)                                                        2067
      BF(IPS,J)=(BO(I,J)+BFIMH+BFJMH-BFIPH-BFJPH)                           2068
      BFR(IPS,J)=(BR(I,J)-BRIJMH+BRFJMH+BRIJPH-BRFJPH)                      2069
      BFZ(IPS,J)=(BZ(I,J)+BZFIMH-BZIJMH-BZFIPH+BZIJPH)                      2070
      BFJMH=BFJPH                                                           2071
      BRFJMH=BRFJPH                                                         2072
      BRIJMH=BRIJPH                                                         2073
      BFA(J)=BFIPH                                                          2074
      BZZA(J)=BZIJPH                                                        2075
      BZFA(J)=BZFIPH                                                        2076
C                                                                           2077
   40 MFA(J)=MFIPH                                                          2078
      UFA(J)=UFIPH                                                          2079
      VFA(J)=VFIPH                                                          2080
      EFA(J)=EFIPH                                                          2081
C     ********************************************************************  2082
C     ********** ASSIGNING VALUES TO RHO,U,V,EB,BR AND BZ **************  2083
C     ************************ AT TIME(N+1) ******************************  2084
C     ********************************************************************  2085
      IF (I.LT.3) GO TO 60                                                  2086
      JH=1                                                                  2087
      IF (I.EQ.KP1) JH=2                                                    2088
      DO 50 JL=1,JH                                                         2089
      N=I-2+JL                                                              2090
      L=IPF                                                                 2091
      IF (JL.EQ.2) L=IPS                                                    2092
      RHO(N,J)=RHOF(L,J)                                                    2093
      U(N,J)=UF(L,J)                                                        2094
      V(N,J)=VF(L,J)                                                        2095
      IF (ABS(U(N,J)).LT.0.00001) U(N,J)=0.                                 2096
      IF (ABS(V(N,J)).LT.0.00001) V(N,J)=0.                                 2097
      E(N,J)=EF(L,J)                                                        2098
C                                                                           2099
      IF (EMF.NE.1) GO TO 50                                                2100
      BO(N,J)=BF(L,J)                                                       2101
      BR(N,J)=BFR(L,J)                                                      2102
      BZ(N,J)=BFZ(L,J)                                                      2103
   50 CONTINUE                                                              2104
   60 CONTINUE                                                              2105
      RETURN                                                                2106
      END                                                                   2107
      SUBROUTINE EFIELD                                                     2108
C                                                                           2109
C                                                                           2110
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  2111
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C     SOLVES ELECTRIC POTENTIAL OR STREAM FUNCTION ELLIPTIC PDE                2112
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  2113
C                                                                              2114
C                                                                              2115
C     DIMENSION COEF1(45,225),COEF2(45,225),COEF3(45,225),COEF4(45,225),       2116
C    1COEF5(45,225)                                                            2117
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,        2118
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                     2119
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                                 2120
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ        2121
      COMMON /GRAVTY/ GC,GR,GZ                                                 2122
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX                  2123
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D       2124
     1ZO,DRO,IGRAPH(225),NBOUND                                                2125
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF                  2126
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM       2127
     1,NVECT,NPDIM                                                             2128
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX        2129
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225       2130
     1),DIAG(225),SUP(225),CONST(225)                                          2131
      REAL*8 R,RD                                                              2132
      ITER=0                                                                   2133
   10 CONTINUE                                                                 2134
      ITER=ITER+1                                                              2135
      ID=1                                                                     2136
      JD=1                                                                     2137
      DIFMAX=0.                                                                2138
C                                                                              2139
C                                                                              2140
C     ***************************************************************          2141
C     ********** FOR SOR, OMEGA=1.75. FOR GAUSS-SEIDEL, OMEGA=1.0. *******    2142
C     ***************************************************************          2143
      OMEGA=1.75                                                               2144
      DO 80 J=2,JP1                                                            2145
      IX=KP2-IOBL(J)+2                                                         2146
      IY=IOBL(J)-1                                                             2147
      IF(IX.LE.1.OR.IY.GE.KP2) WRITE(6,120)                                    2148
      DO 70 I=IX,IY                                                            2149
C     IF(ITER.GT.1) GO TO 55                                                   2150
      DR2=1./((R(I)-R(I-1))*DR(I))                                             2151
      DR1=1./((R(I+1)-R(I))*DR(I))                                             2152
      DBETA=(BETA(I,J,0,1)-BETA(I,J,0,-1))/DZ(J)                               2153
      BBR=+DR1+DR2                                                             2154
C     ***************************************************************          2155
      UIPH=(U(I,J)+U(I+1,J))/2.                                                2156
      UJPH=(U(I,J)+U(I,J+1))/2.                                                2157
      UJMH=(U(I,J)+U(I,J-1))/2.                                                2158
      VJPH=(V(I,J)+V(I,J+1))/2.                                                2159
      VJMH=(V(I,J)+V(I,J-1))/2.                                                2160
      BJPH=(B(I,J)+B(I,J+1))/2.                                                2161
      BJMH=(B(I,J)+B(I,J-1))/2.                                                2162
      UIMH=(U(I,J)+U(I-1,J))/2.                                                2163
      VIPH=(V(I,J)+V(I+1,J))/2.                                                2164
      VIMH=(V(I,J)+V(I-1,J))/2.                                                2165
      BIPH=(B(I,J)+B(I+1,J))/2.                                                2166
      BIMH=(B(I,J)+B(I-1,J))/2.                                                2167
C                                                                              2168
      IF (IPTSF.NE.2) GO TO 20                                                 2169
      DCOND1=(SIG(I,J,1,0,1)-SIG(I,J,-1,0,1))/(DR(I)*SIG(I,J,0,0,1))           2170
      DCOND2=(SIG(I,J,0,1,1)-SIG(I,J,0,-1,1))/(DZ(J)*SIG(I,J,0,0,1))           2171
      A=(DR1+1./(2.*DR(I))*(DCOND1-BETA(I,J,0,0)*DCOND2-DBETA))                2172
      C=(DR2-1./(2.*DR(I))*(DCOND1-BETA(I,J,0,0)*DCOND2-DBETA))                2173
      D=((U(I,J)*B(I,J)-BETA(I,J,0,0)*V(I,J)*B(I,J))*DCOND1-(UIPH*BIPH-B       2174
     1ETA(I,J,1,0)*VIPH*BIPH-UIMH*BIMH+BETA(I,J,-1,0)*VIMH*BIMH)/DR(I))        2175
```

```
      GO TO 30                                                          2176
C                                                                       2177
   20 DCOND1=(SIG(I,J,1,0,0)-SIG(I,J,-1,0,0))/(DR(I)*SIG(I,J,0,0,0))    2178
      DCOND2=(SIG(I,J,0,1,0)-SIG(I,J,0,-1,0))/(DZ(J)*SIG(I,J,0,0,0))    2179
      A=(DR1+1./(2.*DR(I))*(-DCOND1-BETA(I,J,0,0)*DCOND2+DBETA))        2180
      C=(DR2-1./(2.*DR(I))*(-DCOND1-BETA(I,J,0,0)*DCOND2+DBETA))        2181
      D=-SIG(I,J,0,0,0)*(BJPH*UJPH-BJMH*UJMH)/DZ(J)                     2182
C                                                                       2183
   30 DZ1=1./((Z(J+1)-Z(J))*DZ(J))                                      2184
      DZ2=1./((Z(J)-Z(J-1))*DZ(J))                                      2185
      DBETA=(BETA(I,J,1,0)-BETA(I,J,-1,0))/DR(I)                        2186
      BP=+DZ1+DZ2                                                       2187
C                                                                       2188
      IF (IPTSF.NE.2) GO TO 40                                          2189
      DCOND1=(SIG(I,J,0,1,1)-SIG(I,J,0,-1,1))/(DZ(J)*SIG(I,J,0,0,1))    2190
      DCOND2=(SIG(I,J,1,0,1)-SIG(I,J,-1,0,1))/(DR(I)*SIG(I,J,0,0,1))    2191
      AP=(DZ1+1./(2.*DZ(J))*(DCOND1+BETA(I,J,0,0)*DCOND2+DBETA))        2192
      CP=(DZ2-1./(2.*DZ(J))*(DCOND1+BETA(I,J,0,0)*DCOND2+DBETA))        2193
      DP=(-(V(I,J)*B(I,J)+BETA(I,J,0,0)*U(I,J)*B(I,J))*DCOND1+(VJPH*BJPH 2194
     1+BETA(I,J,0,1)*UJPH*BJPH-VJMH*BJMH-BETA(I,J,0,-1)*UJMH*BJMH)/DZ(J) 2195
     2)                                                                 2196
      GO TO 50                                                          2197
C                                                                       2198
   40 DCOND1=(SIG(I,J,0,1,0)-SIG(I,J,0,-1,0))/(DZ(J)*SIG(I,J,0,0,0))    2199
      DCOND2=(SIG(I,J,1,0,0)-SIG(I,J,-1,0,0))/(DR(I)*SIG(I,J,0,0,0))    2200
      AP=(DZ1+1./(2.*DZ(J))*(-DCOND1+BETA(I,J,0,0)*DCOND2-DBETA))       2201
      CP=(DZ2-1./(2.*DZ(J))*(-DCOND1+BETA(I,J,0,0)*DCOND2-DBETA))       2202
      DP=-SIG(I,J,0,0,0)*(BIPH*VIPH-BIMH*VIMH)/DR(I)                    2203
C                                                                       2204
   50 CONTINUE                                                          2205
C     ********************************************************************2206
C     COEF1,.....COEF5 ARE ARRAYS, WHICH WHEN USED, WILL REDUCE THE     2207
C     CONVERGENCE TIME (CP) BY A FACTOR OF 3 OR 4 AT THE EXPENSE OF     2208
C     ADDITIONAL CORE.                                                  2209
C     ********************************************************************2210
C     COEF1(I,J)=(-D-DP)/(BBR+BP)                                       2211
C     COEF2(I,J)=A/(BBR+BP)                                             2212
C     COEF3(I,J)=AP/(BBR+BP)                                            2213
C     COEF4(I,J)=C/(BBR+BP)                                             2214
C     COEF5(I,J)=CP/(BBR+BP)                                            2215
   55 IF (I.EQ.IX.OR.I.EQ.IY.OR.J.EQ.2.OR.J.EQ.JP1) CALL BNDPOT (I,J)   2216
      OLDPHI=PHI(I,J)                                                   2217
      PHI(I,J)=(-D-DP+A*PHI(I+1,J)+AP*PHI(I,J+1)+C*PHI(I-1,J)+CP*PHI(I,J 2218
     1-1))/(BBR+BP)                                                     2219
C     PHI(I,J)=COEF1(I,J)+COEF2(I,J)*PHI(I+1,J)+COEF3(I,J)*PHI(I,J+1)+  2220
C     1COEF4(I,J)*PHI(I-1,J)+COEF5(I,J)*PHI(I,J-1)                      2221
      PHI(I,J)=PHI(I,J)*OMEGA+(1.-OMEGA)*OLDPHI                         2222
      DIFF=ABS(PHI(I,J)-OLDPHI)/(5.*SIG(I,J,0,0,0)*U(I,J)*B(I,J))       2223
      IF (DIFF.LE.DIFMAX) GO TO 60                                      2224
      ID=I                                                              2225
      JD=J                                                              2226
      OLDIE=OLDPHI                                                      2227
      GOODIE=PHI(I,J)                                                   2228
      DIFMAX=DIFF                                                       2229
   60 CONTINUE                                                          2230
   70 CONTINUE                                                          2231
   80 CONTINUE                                                          2232
C                                                                       2233
      DO 100 J=2,JP1                                                    2234
      I1=KP2-IOBL(J)+2                                                  2235
      I2=IOBL(J)-1                                                      2236
      DO 90 I=I1,I2                                                     2237
      IF (I.EQ.I1.OR.I.EQ.I2.OR.J.EQ.2.OR.J.EQ.JP1) CALL BNDPOT (I,J)   2238
   90 CONTINUE                                                          2239
```

```
  100 CONTINUE                                                          2240
      WRITE (6,110) ID,JD,DIFMAX,ITER                                   2241
      IF (ITER.GT.100) RETURN                                           2242
      IF (DIFMAX.GT..0010) GO TO 10                                     2243
      RETURN                                                            2244
C                                                                       2245
C                                                                       2246
  110 FORMAT (35H ELECTRICAL CONVERGENCE ....AT CELL,2(1X,I3),15H  DIFFE 2247
     1RENCE = ,E12.4,3X,15HFOR ITERATION  ,I3)                          2248
  120 FORMAT(85H   ELECTRODES CANNOT LIE ON THE BOUNDARY..... REDUCE "RD 2249
     1 S" BY 1 OR 2 "DRO S"          )                                  2250
      END                                                               2251
      SUBROUTINE CURRNT (JZ,JR,EZ,ER,UU,VV,I,J,IHALF,JHALF)             2252
C                                                                       2253
C                                                                       2254
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2255
C     COMPUTES ELECTRIC FIELD AND CURRENT BASED ON THE STREAM CURRENT   2256
C     FUNCTION, POTENTIAL OR INDUCED MAGNETIC FIELD                     2257
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2258
C                                                                       2259
C                                                                       2260
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 2261
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                              2262
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                          2263
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 2264
      COMMON /GRAVTY/ GC,GR,GZ                                          2265
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX           2266
      COMMON/CGRID/R(45),RO(45),Z(225),DR(45),DZ(225),XO(45),ZMIN,RMIN,D 2267
     1ZO,DRO,IGRAPH(225),NBOUND                                         2268
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF           2269
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM 2270
     1,NVECT,NPOIM                                                      2271
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX 2272
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225 2273
     1),DIAG(225),SUP(225),CONST(225)                                   2274
      REAL*8 R,RO                                                       2275
      REAL JR,JZ                                                        2276
C                                                                       2277
C                                                                       2278
      EZ=0.                                                             2279
      ER=EZ                                                             2280
      JZ=ER                                                             2281
      JR=JZ                                                             2282
      IF (I.EQ.1.OR.I.EQ.KP2.OR.J.EQ.1.OR.J.EQ.JP2) RETURN              2283
      IF (EMF.EQ.1) GO TO 20                                            2284
      DPHIR=((PHI(I+1,J)-PHI(I-1,J))+JHALF*(PHI(I+1,J+1)-PHI(I-1,J+1))+I 2285
     1HALF*(PHI(I-1,J)-PHI(I,J)))/(R(I+1)-R(I-1)+JHALF*(R(I-1)-R(I+1)+4. 2286
     2*DR(I))+IHALF*(R(I-1)-R(I)))                                      2287
      DPHIZ=((PHI(I,J+1)-PHI(I,J-1))+IHALF*(PHI(I+1,J+1)-PHI(I+1,J-1))+J 2288
     1HALF*(PHI(I,J-1)-PHI(I,J)))/(Z(J+1)-Z(J-1)+IHALF*(Z(J-1)+Z(J+1)+4. 2289
     2*DZ(J))+JHALF*(Z(J-1)-Z(J)))                                      2290
      IF (IPTSF.EQ.2) GO TO 10                                          2291
C     ********************************************************************** 2292
C     ********************* CURRENT STREAM FUNCTION ********************** 2293
C     ********************************************************************** 2294
      JZ=DPHIR                                                          2295
      JR=-DPHIZ                                                         2296
      GO TO 20                                                          2297
   10 CONTINUE                                                          2298
C     ********************************************************************** 2299
C     ************************** POTENTIAL ********************************* 2300
C     ********************************************************************** 2301
      JZ=SIG(I,J,IHALF,JHALF,1)*((-DPHIZ+VV*(B(I+IHALF,J+JHALF)+B(I,J))/ 2302
     12.)-BETA(I,J,IHALF,JHALF)*(-DPHIR-UU*(B(I+IHALF,J+JHALF)+B(I,J))/2 2303
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     2.))                                                                    2304
      JR=SIG(I,J,IHALF,JHALF,1)*(BETA(I,J,IHALF,JHALF)*(-DPHIZ+VV*(B(I+I    2305
     1HALF,J+JHALF)+B(I,J))/2.)+(-DPHIR-UU*(B(I+IHALF,J+JHALF)+B(I,J))/2    2306
     2.))                                                                    2307
   20 CONTINUE                                                               2308
C     ************************************************************          2309
C     ********************  INDUCED MAGNETIC FIELD  ********************    2310
C     ************************************************************          2311
      IF (EMF.NE.1) GO TO 30                                                 2312
      JZ=-1./PERMO*(B(I+1,J)-B(I-1,J))/(R(I+1)-R(I-1))                       2313
      JR=1./PERMO*(B(I,J+1)-B(I,J-1))/(Z(J+1)-Z(J-1))                        2314
C     ************************************************************          2315
C     ************  COMPUTING THE ELECTRIC FIELD COMPONENTS  **************  2316
C     ************************************************************          2317
   30 EZ=(JZ+BETA(I,J,IHALF,JHALF)*JR)/SIG(I,J,IHALF,JHALF,0)-VV*(B(I+IH     2318
     1ALF,J+JHALF)+B(I,J))/2.                                                2319
      ER=(JR-BETA(I,J,IHALF,JHALF)*JZ)/SIG(I,J,IHALF,JHALF,0)+UU*(B(I+IH    2320
     1ALF,J+JHALF)+B(I,J))/2.                                                2321
      RETURN                                                                 2322
      END                                                                    2323
      FUNCTION CUR(I,J)                                                      2324
C                                                                            2325
C                                                                            2326
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   2327
C     COMPUTES RADIAL CURRENT INTO AND OUT OF ELECTRODES.                    2328
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   2329
C                                                                            2330
C                                                                            2331
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,      2332
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                   2333
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                               2334
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ      2335
      COMMON /GRAVTY/ GC,GR,GZ                                               2336
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX                2337
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XO(45),ZMIN,RMIN,D     2338
     1ZO,DRO,IGRAPH(225),NBOUND                                              2339
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IOFN,IPTSF                2340
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM     2341
     1,NVECT,NPOIM                                                           2342
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX      2343
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225     2344
     1),DIAG(225),SUP(225),CONST(225)                                        2345
      REAL*8 R,RD                                                            2346
      REAL JR,JRR                                                            2347
C                                                                            2348
C                                                                            2349
      UU=U(I,J)                                                              2350
      VV=V(I,J)                                                              2351
      IHALF=0                                                                2352
      JHALF=0                                                                2353
      DPHIR=((PHI(I+1,J)-PHI(I-1,J))+JHALF*(PHI(I+1,J+1)-PHI(I-1,J+1))+I     2354
     1HALF*(PHI(I-1,J)-PHI(I,J)))/(R(I+1)-R(I-1)+JHALF*(R(I-1)-R(I+1)+4.    2355
     2*DR(I))+IHALF*(R(I-1)-R(I)))                                           2356
      DPHIZ=((PHI(I,J+1)-PHI(I,J-1))+IHALF*(PHI(I+1,J+1)-PHI(I+1,J-1))+J     2357
     1HALF*(PHI(I,J-1)-PHI(I,J)))/(Z(J+1)-Z(J-1)+IHALF*(Z(J-1)+Z(J+1)+4.    2358
     2*DZ(J))+JHALF*(Z(J-1)-Z(J)))                                           2359
      JR=SIG(I,J,IHALF,JHALF,1)*(BETA(I,J,IHALF,JHALF)*(-DPHIZ+VV*(B(I+I     2360
     1HALF,J+JHALF)+B(I,J))/2.)+(-DPHIR-UU*(B(I+IHALF,J+JHALF)+B(I,J))/2    2361
     2.))                                                                    2362
      JRR=JR                                                                 2363
      CUR=JRR                                                                2364
      RETURN                                                                 2365
      END                                                                    2366
      SUBROUTINE DFSN                                                        2367
```

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C                                                                       2368
C                                                                       2369
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2370
C     CALCULATES MAGNETIC DIFFUSION                                     2371
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2372
C                                                                       2373
C                                                                       2374
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 2375
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                              2376
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                          2377
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 2378
      COMMON /GRAVTY/ GC,GR,GZ                                          2379
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX           2380
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 2381
     1ZO,DRO,IGRAPH(225),NBOUND                                         2382
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF           2383
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM 2384
     1,NVECT,NPDIM                                                      2385
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX 2386
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225 2387
     1),DIAG(225),SUP(225),CONST(225)                                   2388
      REAL*8 R,RD,RIPH,RIMH                                             2389
C                                                                       2390
C                                                                       2391
C     ******************************************************************2392
C     MAGNETIC AND THERMAL TRANSPORT                                    2393
C     ******************************************************************2394
      DO 100 IFIELD=1,3                                                 2395
      DO 90 NDT=1,NMAGN                                                 2396
      CALL BOUND                                                        2397
      DO 30 J=2,JP1                                                     2398
      DO 30 I=2,KP1                                                     2399
      RIPH=(R(I)+R(I+1))/2.                                             2400
      RIMH=R(I-1)+DR(I)/2.                                              2401
      T1=DT/((R(I+1)-R(I))*DR(I)*R(I))/NMAGN                            2402
      T2=DT/((R(I)-R(I-1))*DR(I)*R(I))/NMAGN                            2403
      T3=DT/((Z(J+1)-Z(J))*DZ(J))/NMAGN                                 2404
      T4=DT/((Z(J)-Z(J-1))*DZ(J))/NMAGN                                 2405
      IF (IFIELD.GT.1) GO TO 10                                         2406
      DB1=(BO(I+1,J)/SIG(I,J,1,0,0)-BO(I,J)/SIG(I,J,1,0,0))*RIPH        2407
      DB2=(BO(I-1,J)/SIG(I,J,-1,0,0)-BO(I,J)/SIG(I,J,-1,0,0))*RIMH      2408
      DB3=BO(I,J+1)/SIG(I,J,0,1,0)-BO(I,J)/SIG(I,J,0,1,0)               2409
      DB4=BO(I,J-1)/SIG(I,J,0,-1,0)-BO(I,J)/SIG(I,J,0,-1,0)             2410
      DE(I,J)=(T1*DB1+T2*DB2+T3*DB3+T4*DB4)/PERM                        2411
   10 IF (IFIELD.NE.2) GO TO 20                                         2412
      DBR1=(BR(I+1,J)/SIG(I,J,+1,0,0)-BR(I,J)/SIG(I,J,+1,0,0))*RIPH     2413
      DBR2=(BR(I-1,J)/SIG(I,J,-1,0,0)-BR(I,J)/SIG(I,J,-1,0,0))*RIMH     2414
      DBR3=BR(I,J+1)/SIG(I,J,0,+1,0)-BR(I,J)/SIG(I,J,0,+1,0)            2415
      DBR4=BR(I,J-1)/SIG(I,J,0,-1,0)-BR(I,J)/SIG(I,J,0,-1,0)            2416
      DE(I,J)=(T1*DBR1+T2*DBR2+T3*DBR3+T4*DBR4)/PERM                    2417
   20 IF (IFIELD.NE.3) GO TO 30                                         2418
      DBZ1=(BZ(I+1,J)/SIG(I,J,+1,0,0)-BZ(I,J)/SIG(I,J,+1,0,0))*RIPH     2419
      DBZ2=(BZ(I-1,J)/SIG(I,J,-1,0,0)-BZ(I,J)/SIG(I,J,-1,0,0))*RIMH     2420
      DBZ3=BZ(I,J+1)/SIG(I,J,0,+1,0)-BZ(I,J)/SIG(I,J,0,+1,0)            2421
      DBZ4=BZ(I,J-1)/SIG(I,J,0,-1,0)-BZ(I,J)/SIG(I,J,0,-1,0)            2422
      DE(I,J)=(T1*DBZ1+T2*DBZ2+T3*DBZ3+T4*DBZ4)/PERM                    2423
   30 CONTINUE                                                          2424
      IF (IDFN.EQ.2) GO TO 100                                          2425
C                                                                       2426
C     ******************************************************************2427
C     MAGNETIC DIFFUSION                                                2428
C     ******************************************************************2429
      IF (IFIELD.GT.1) GO TO 50                                         2430
      DO 40 I=2,KP1                                                     2431
```

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      DO 40 J=2,JP1                                                          2432
      BO(I,J)=BO(I,J)+DE(I,J)                                                2433
   40 CONTINUE                                                               2434
   50 IF (IFIELD.NE.2) GO TO 70                                              2435
      DO 60 I=2,KP1                                                          2436
      DO 60 J=2,JP1                                                          2437
      BR(I,J)=BR(I,J)+DE(I,J)                                                2438
   60 CONTINUE                                                               2439
   70 IF (IFIELD.NE.3) GO TO 90                                              2440
      DO 80 I=2,KP1                                                          2441
      DO 80 J=2,JP1                                                          2442
      BZ(I,J)=BZ(I,J)+DE(I,J)                                                2443
   80 CONTINUE                                                               2444
   90 CONTINUE                                                               2445
  100 CONTINUE                                                               2446
      CALL SECOND (A)                                                        2447
C                                                                            2448
      IF (IDFN.EQ.1) GO TO 140                                               2449
C     ***************************************************************        2450
C     THERMAL CONDUCTION                                                     2451
C     ***************************************************************        2452
      DO 130 NDT=1,NTHRM                                                     2453
      CALL BOUND                                                             2454
      DO 110 I=2,KP1                                                         2455
      RIPH=(R(I)+R(I+1))/2.                                                  2456
      RIMH=(R(I)+R(I-1))/2.                                                  2457
      DO 110 J=2,JP1                                                         2458
      T=(E(I,J)-0.5*(U(I,J)**2+V(I,J)**2))/CV(I,J,0,0)                       2459
      TP1=(E(I+1,J)-0.5*(U(I+1,J)**2+V(I+1,J)**2))/CV(I+1,J,0,0)             2460
      TM1=(E(I-1,J)-0.5*(U(I-1,J)**2+V(I-1,J)**2))/CV(I-1,J,0,0)             2461
      TP2=(E(I,J+1)-0.5*(U(I,J+1)**2+V(I,J+1)**2))/CV(I,J+1,0,0)             2462
      TM2=(E(I,J-1)-0.5*(U(I,J-1)**2+V(I,J-1)**2))/CV(I,J-1,0,0)             2463
      T1=DT/((R(I+1)-R(I))*DR(I)*R(I))/NTHRM                                 2464
      T2=DT/((R(I)-R(I-1))*DR(I)*R(I))/NTHRM                                 2465
      T3=DT/((Z(J+1)-Z(J))*DZ(J))/NTHRM                                      2466
      T4=DT/((Z(J)-Z(J-1))*DZ(J))/NTHRM                                      2467
      DT1=(TP1*COND(I,J,+1,0)-T*COND(I,J,+1,0))*RIPH                         2468
      DT2=(TM1*COND(I,J,-1,0)-T*COND(I,J,-1,0))*RIPH                         2469
      DT3=TP2*COND(I,J,0,+1)-T*COND(I,J,0,+1)                                2470
      DT4=TM2*COND(I,J,0,-1)-T*COND(I,J,0,-1)                                2471
      DE(I,J)=(T1*DT1+T2*DT2+T3*DT3+T4*DT4)/RHO(I,J)                         2472
  110 CONTINUE                                                               2473
      DO 120 I=2,KP1                                                         2474
      DO 120 J=2,JP1                                                         2475
  120 E(I,J)=E(I,J)+DE(I,J)                                                  2476
  130 CONTINUE                                                               2477
  140 CONTINUE                                                               2478
      RETURN                                                                 2479
      END                                                                    2480
      SUBROUTINE TEMDIF                                                      2481
C                                                                            2482
C                                                                            2483
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   2484
C     CALCULATES THERMAL DIFFUSION IMPLICITLY                                2485
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX   2486
C                                                                            2487
C                                                                            2488
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,      2489
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                   2490
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                               2491
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ      2492
      COMMON /GRAVTY/ GC,GR,GZ                                               2493
      COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX                2494
      COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D     2495
```

```
     1ZO,DRO,IGRAPH(225),NBOUND                                          2496
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF            2497
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM 2498
     1,NVECT,NPOIM                                                       2499
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX  2500
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225 2501
     1),DIAG(225),SUP(225),CONST(225)                                    2502
      REAL*8 R,RO                                                        2503
C                                                                        2504
C                                                                        2505
      DO 20 J=2,JP1                                                      2506
      DO 10 K=2,KP1                                                      2507
      I=K                                                                2508
      ENERGY=E(K,J)-0.5*(U(K,J)**2+V(K,J)**2)                            2509
      DR1=1./((R(K+1)-R(K))*DR(K))                                       2510
      DR2=1./((R(K)-R(K-1))*DR(K))                                       2511
      DCOND1=1./(COND(K,J,0,0)*DZ(J))*(COND(K,J,0,1)-COND(K,J,0,-1))     2512
      ALPHA=RHO(K,J)*CV(K,J,0,0)/COND(K,J,0,0)                           2513
      ACOEF(I-1)=DR1+1./(2.*DR(K))*DCOND1                                2514
      BCOEF(I-1)=-DR1-DR2-ALPHA/DT                                       2515
      CCOEF(I-1)=DR2-1./(2.*DR(K))*DCOND1                                2516
      DCOEF(I-1)=-ALPHA/DT*ENERGY/CV(K,J,0,0)                            2517
   10 CONTINUE                                                           2518
      CALL KSWEEP (J)                                                    2519
   20 CONTINUE                                                           2520
      DO 40 K=2,KP1                                                      2521
      DO 30 J=2,JP1                                                      2522
      ENERGY=E(K,J)-0.5*(U(K,J)**2+V(K,J)**2)                            2523
      DZ1=1./((Z(J+1)-Z(J))*DZ(J))                                       2524
      DZ2=1./((Z(J)-Z(J-1))*DZ(J))                                       2525
      DCOND1=1./(COND(K,J,0,0)*DR(K))*(COND(K,J,1,0)-COND(K,J,-1,0))     2526
      ALPHA=RHO(K,J)*CV(K,J,0,0)/COND(K,J,0,0)                           2527
      ACOEF(J-1)=DZ1+1./(2.*DZ(J))*DCOND1                                2528
      BCOEF(J-1)=-DZ1-DZ2-ALPHA/DT                                       2529
      CCOEF(J-1)=DZ2-1./(2.*DZ(J))*DCOND1                                2530
      DCOEF(J-1)=-ALPHA/DT*ENERGY/CV(K,J,0,0)                            2531
   30 CONTINUE                                                           2532
      CALL JSWEEP (K)                                                    2533
   40 CONTINUE                                                           2534
      RETURN                                                             2535
      END                                                                2536
      SUBROUTINE TRID (M)                                                2537
C                                                                        2538
C                                                                        2539
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2540
C     SETS-UP TRI-DIAGONAL MATRIX FOR IMPLICIT INTEGRATION               2541
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2542
C                                                                        2543
C                                                                        2544
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225 2545
     1),DIAG(225),SUP(225),CONST(225)                                    2546
C                                                                        2547
      N=M                                                                2548
      NN=N-1                                                             2549
      SUP(1)=SUP(1)/DIAG(1)                                              2550
      CONST(1)=CONST(1)/DIAG(1)                                          2551
      DO 10 I=2,N                                                        2552
      II=I-1                                                             2553
      DIAG(I)=DIAG(I)-SUP(II)*SUB(I)                                     2554
      IF (I.EQ.N) GO TO 10                                               2555
      SUP(I)=SUP(I)/DIAG(I)                                              2556
   10 CONST(I)=(CONST(I)-SUB(II)*CONST(II))/DIAG(I)                      2557
      DO 20 K=1,NN                                                       2558
      I=N-K                                                              2559
```

```
      CONST(I)=CONST(I)-SUP(I)*CONST(I+1)                                    2560
   20 CONTINUE                                                               2561
      RETURN                                                                 2562
      END                                                                    2563
      SUBROUTINE KSWEEP (J)                                                  2564
C                                                                            2565
C                                                                            2566
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  2567
C     IMPLICIT SWEEP IN THE K DIRECTION                                      2568
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  2569
C                                                                            2570
C                                                                            2571
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,      2572
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                   2573
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                               2574
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225     2575
     1),DIAG(225),SUP(225),CONST(225)                                        2576
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF                2577
C                                                                            2578
C                                                                            2579
      IF (IDFN.NE.1) GO TO 10                                                2580
      DCOEF(1)=DCOEF(1)-CCOEF(1)*PHI(1,J)                                    2581
      DCOEF(KMAX)=DCOEF(KMAX)-ACOEF(KMAX)*PHI(KP2,J)                         2582
      GO TO 20                                                               2583
   10 ENER1=E(1,J)-0.5*(U(1,J)**2+V(1,J)**2)                                 2584
      ENER2=E(KP2,J)-0.5*(U(KP2,J)**2+V(KP2,J)**2)                           2585
      DCOEF(1)=DCOEF(1)-CCOEF(1)*ENER1/CV(1,J,0,0)                           2586
      DCOEF(KMAX)=DCOEF(KMAX)-ACOEF(KMAX)*ENER2/CV(KP2,J,0,0)                2587
   20 CONTINUE                                                               2588
      DO 30 K=1,KMAX                                                         2589
      INDEX=KMAX-K+1                                                         2590
      DIAG(INDEX)=BCOEF(K)                                                   2591
      SUP(INDEX)=CCOEF(K)                                                    2592
      SUB(INDEX)=ACOEF(K)                                                    2593
      CONST(INDEX)=DCOEF(K)                                                  2594
   30 CONTINUE                                                               2595
      CALL TRID (KMAX)                                                       2596
      DO 40 K=1,KMAX                                                         2597
      L=KMAX-K+1                                                             2598
      DE(K+1,J)=CONST(L)                                                     2599
   40 CONTINUE                                                               2600
      RETURN                                                                 2601
C                                                                            2602
      END                                                                    2603
      SUBROUTINE JSWEEP (K)                                                  2604
C                                                                            2605
C                                                                            2606
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  2607
C     IMPLICIT SWEEP IN THE J DIRECTION                                      2608
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  2609
C                                                                            2610
C                                                                            2611
      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,      2612
     1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                   2613
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                               2614
      COMMON/CMATRX/ ACOEF(225),BCOEF(225),CCOEF(225),DCOEF(225),SUB(225     2615
     1),DIAG(225),SUP(225),CONST(225)                                        2616
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF                2617
C                                                                            2618
C                                                                            2619
      IF (IDFN.NE.1) GO TO 10                                                2620
      DCOEF(1)=DCOEF(1)-CCOEF(1)*PHI(K,1)                                    2621
      DCOEF(JMAX)=DCOEF(JMAX)-ACOEF(JMAX)*PHI(K,JP2)                         2622
      GO TO 20                                                               2623
```

```
   10 ENER1=E(K,1)-0.5*(U(K,1)**2+V(K,1)**2)                                2624
      ENER2=E(K,JP2)-0.5*(U(K,JP2)**2+V(K,JP2)**2)                          2625
      DCOEF(1)=DCOEF(1)-CCOEF(1)*ENER1/CV(K,1,0,0)                          2626
      DCOEF(JMAX)=DCOEF(JMAX)-ACOEF(JMAX)*ENER2/CV(K,JP2,0,0)               2627
   20 CONTINUE                                                              2628
      DO 30 J=1,JMAX                                                        2629
      INDEX=JMAX-J+1                                                        2630
      DIAG(INDEX)=BCOEF(J)                                                  2631
      SUP(INDEX)=CCOEF(J)                                                   2632
      SUB(INDEX)=ACOEF(J)                                                   2633
      CONST(INDEX)=DCOEF(J)                                                 2634
   30 CONTINUE                                                              2635
      CALL TRID (JMAX)                                                      2636
      DO 40 J=1,JMAX                                                        2637
      L=JMAX-J+1                                                            2638
      DE(K,J+1)=DE(K,J+1)+CONST(L)                                          2639
   40 CONTINUE                                                              2640
      RETURN                                                                2641
      END                                                                   2642
      FUNCTION GAMM(I,J)                                                    2643
C                                                                           2644
C                                                                           2645
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2646
C     DEFINES SPECIFIC HEAT RATIO                                           2647
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2648
C                                                                           2649
C                                                                           2650
      GAMM=1.15                                                             2651
      RETURN                                                                2652
      END                                                                   2653
      FUNCTION RGAS(P,T)                                                    2654
C                                                                           2655
C                                                                           2656
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2657
C     GAS CONSTANT                                                          2658
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2659
C                                                                           2660
C                                                                           2661
      RGAS=4.184*10.**7*1.987/22.                                           2662
      RETURN                                                                2663
      END                                                                   2664
      FUNCTION CV(I,J,IHALF,JHALF)                                          2665
C                                                                           2666
C                                                                           2667
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF               2668
C     DEFINES SPECIFIC HEAT AT CONSTANT VOLUME                              2669
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2670
C                                                                           2671
C                                                                           2672
      CV=1.67*10.**7                                                        2673
      RETURN                                                                2674
      END                                                                   2675
      FUNCTION CP(P,T)                                                      2676
C                                                                           2677
C                                                                           2678
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2679
C     DEFINES SPECIFIC HEAT AT CONSTANT PRESSURE                            2680
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2681
C                                                                           2682
C                                                                           2683
      H=-0.22016E8-0.27793E2*P+0.23314E-4*P**2+(-0.16712E5+0.28226E-1*P-    2684
     10.23821E-7*P**2)*T+(0.44858E1-0.71655E-5*P+0.60721E-11*P**2)*T**2     2685
      CP=H/T                                                                2686
      RETURN                                                                2687
```

```
      END                                                                2688
      FUNCTION VIS(I,J,IHALF,JHALF)                                      2689
C                                                                        2690
C                                                                        2691
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2692
C     COMPUTES LAMINAR VISCOSITY                                         2693
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2694
C                                                                        2695
C                                                                        2696
      COMMON/CSTRSS/TRRA(225),TZZA(225),TOOA(225),TRZA(225),VISC,VISCO   2697
C                                                                        2698
C                                                                        2699
      VISC=VISCO                                                         2700
      VIS=VISCO                                                          2701
      RETURN                                                             2702
      END                                                                2703
      FUNCTION EDDY(I,J)                                                 2704
C                                                                        2705
C                                                                        2706
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2707
C     EDDY COEFFICIENT FOR TURBULENT CALCULATION                         2708
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2709
C                                                                        2710
C                                                                        2711
      EDDY=0.                                                            2712
      RETURN                                                             2713
      END                                                                2714
      FUNCTION COND(K,J,KHALF,JHALF)                                     2715
C                                                                        2716
C                                                                        2717
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2718
C     DEFINES THERMAL CONDUCTIVITY                                       2719
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2720
C                                                                        2721
C                                                                        2722
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF            2723
      NTHRM=99999                                                        2724
      COND=0.                                                            2725
      RETURN                                                             2726
      END                                                                2727
      FUNCTION SIG(I,J,IHALF,JHALF,IN)                                   2728
C                                                                        2729
C                                                                        2730
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2731
C     DEFINES ELECTRICAL CONDUCTIVITY                                    2732
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2733
C                                                                        2734
C                                                                        2735
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF            2736
C                                                                        2737
C                                                                        2738
      NMAGN=99999                                                        2739
      SIG=10.**(-10)                                                     2740
      RETURN                                                             2741
      END                                                                2742
      FUNCTION BETA(I,J,IHALF,JHALF)                                     2743
C                                                                        2744
C                                                                        2745
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2746
C     DEFINES HALL PARAMETER                                             2747
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2748
C                                                                        2749
C                                                                        2750
      BETA=2.0                                                           2751
```

```
      RETURN                                                            2752
      END                                                               2753
      FUNCTION B(I,J)                                                   2754
      B=20000.                                                          2755
      RETURN                                                            2756
      END                                                               2757
      SUBROUTINE SECOND (A)                                             2758
      RETURN                                                            2759
      END                                                               2760
      SUBROUTINE PLOTTE                                                 2761
C                                                                       2762
C                                                                       2763
C     THE FOLLOWING SUBROUTINES EMPLOY EITHER STANDARD CALCOMP          2764
C     OR STROMBERG-CARLSON PLOT SUBROUTINES. IF CALCOMP ROUTINES ARE    2765
C     USED THEN THE SC ROUTINES MUST BE DUMMIED OUT (SEE TECHNICAL      2766
C     REPORT) OR IF THE SC ROUTINES ARE USED. THE CALCOMP ROUTINES      2767
C     ARE VOIDED.                                                       2768
C                                                                       2769
C                                                                       2770
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2771
C     PLOT EXECUTIVE ROUTINE                                            2772
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2773
C                                                                       2774
C                                                                       2775
      COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTDL,TZERO,T                 2776
      COMMON/P1/XGRAPH(45),ZGRAPH(225),XVELT(45,225),ZVELT(45,225),     2777
     1SH(45,225),DR(45),DZ(225), NOLIN1(45,225),NOLIN2(45,225),ILOW,    2778
     1IHIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC, 2779
     2DMN(525),XLF(225),YLF(225),IPLOW,IPHIGH,JPLOW,JPHIGH,XPT(50,11),  2780
     3YPT(50,11)                                                        2781
      COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR 2782
     1MIN(10),JRMAX(10),MPODE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG  2783
      COMMON /P3/ ZZ,LI1,LI2,LI3,LI4,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL 2784
     1O,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M 2785
     2OVIE,IDET,IVEL,RPV,ILINE,MZODE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20 2786
     3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM                 2787
C                                                                       2788
C                                                                       2789
C     ********************************************************************** 2790
   10 CONTINUE                                                          2791
C     ********************************************************************** 2792
C     INITIALIZATION                                                    2793
C     ********************************************************************** 2794
      IKT=0                                                             2795
      LI1=0                                                             2796
      LI3=0                                                             2797
      MFR=0                                                             2798
      PLO=0.                                                            2799
      KL1=0                                                             2800
      KL2=0                                                             2801
      KL3=0                                                             2802
      KL4=0                                                             2803
C     ********************************************************************** 2804
C     CARD INPUT DESCRIBING PLOTS DESIRED                               2805
C     ********************************************************************** 2806
      TZERO=0.                                                          2807
      CALL RDPLT                                                        2808
      REWIND 14                                                         2809
   20 CONTINUE                                                          2810
      IF (IHIST.LT.1.AND.ISPAT.LT.1) WRITE (6,150) IVEL,MOVIE,ISC       2811
      IF (IHIST.LT.1.AND.ISPAT.LT.1) CALL GRIDS                         2812
      IF (IHIST.LT.1.AND.ISPAT.LT.1.AND.T.LE.TPLTMA) GO TO 20           2813
C     ********************************************************************** 2814
C     TIME HISTORY                                                      2815
```

```
C     ********************************************************************  2816
      IF (IHIST.EQ.0) GO TO 80                                              2817
      IKT=0                                                                 2818
      IKM=IHIST                                                             2819
      DO 70 KZ=1,IHIST                                                      2820
      MFR=MFRAME(KZ,1)                                                      2821
      IKT=IKT+1                                                             2822
      PLO=1.                                                                2823
      KL1=IHMIN(KZ)                                                         2824
      KL2=IHMAX(KZ)                                                         2825
      KL3=JHMIN(KZ)                                                         2826
      KL4=JHMAX(KZ)                                                         2827
C     ********************************************************************  2828
C     KL1,KL2 AND KL3,KL4 ARE THE CELL INDICES WHERE TIME HISTORIES         2829
C     ARE RECORDED                                                          2830
C     ********************************************************************  2831
      DO 60 IR=KL1,KL2                                                      2832
      DO 60 JR=KL3,KL4                                                      2833
      TZERO=-TPLTDE                                                         2834
      ICODE=MCODE(KZ)                                                       2835
      REWIND 14                                                             2836
      KL=1                                                                  2837
      PRINT 160, KL1,KL2,KL3,KL4,ICODE                                      2838
C     ********************************************************************  2839
C     BLOCKED DATA ON UNIT 14, 36 VARIABLES (TABLE C.1 OF TECHNICAL         2840
C     REPORT) X 14 CELLS                                                    2841
C     ********************************************************************  2842
   30 READ (14) (DMN(KX),KX=1,504),T,NCYCLE,DT                              2843
      DO 40 MX=1,14                                                         2844
      IND=(MX-1)*36                                                         2845
      IA=DMN(IND+1)                                                         2846
      JA=DMN(IND+2)                                                         2847
      DUMVAR(21)=DMN(IND+21)                                                2848
      IC=IND+ICODE                                                          2849
      DUMVAR(ICODE)=DMN(IC)                                                 2850
      IF (T.LT.TPLTMI) GO TO 30                                             2851
      IF (IA.EQ.IR.AND.JA.EQ.JR) XLF(KL)=DUMVAR(21)                         2852
      IF (IA.EQ.IR.AND.JA.EQ.JR) YLF(KL)=DUMVAR(ICODE)                      2853
      IF (IA.EQ.IR.AND.JA.EQ.JR) KL=KL+1                                    2854
      IF (IA.EQ.IR.AND.JA.EQ.JR) PRINT 180, IA,JA,KL,XLF(KL-1),YLF(KL-1)    2855
   40 CONTINUE                                                              2856
      IF (T.LT.TPLTMA) GO TO 30                                             2857
      TZERO=T                                                               2858
      REWIND 14                                                             2859
C     ********************************************************************  2860
C     GRID IS ALSO PLOTTED                                                  2861
C     ********************************************************************  2862
   50 CALL GRIDS                                                            2863
      IF (T.LT.TZERO) GO TO 50                                              2864
      ICH=KL-2                                                              2865
      NIP=0                                                                 2866
      CALL LABPLT (ICH,ICODE,IR,JR,NIP)                                     2867
   60 CONTINUE                                                              2868
   70 CONTINUE                                                              2869
C     ********************************************************************  2870
C     SPATIAL DISTRIBUTUION                                                 2871
C     ********************************************************************  2872
   80 IF (ISPAT.EQ.0) GO TO 140                                             2873
      IKT=0                                                                 2874
      IKM=ISPAT                                                             2875
      DO 130 I=1,ISPAT                                                      2876
      MFR=MFRAME(I,2)                                                       2877
      IKT=IKT+1                                                             2878
      IDIST=3                                                               2879
```

```
      IF (MDIM(I).EQ.2) IDIST=2                                          2880
      PLO=2.                                                             2881
      KL1=IZMIN(I)                                                       2882
      KL2=IZMAX(I)                                                       2883
      KL3=JZMIN(I)                                                       2884
      KL4=JZMAX(I)                                                       2885
      TZERO=0.                                                           2886
      ICODE=MZODE(I)                                                     2887
      REWIND 14                                                          2888
      KL=1                                                               2889
      PRINT 170, KL1,KL2,KL3,KL4,ICODE,IDIST                             2890
   90 READ (14) (DMN(KX),KX=1,504),T,NCYCLE,DT                           2891
      IF (T.LT.TPLTMI) GO TO 90                                          2892
      SUM=T-TPLTOL-TZERO                                                 2893
      IF (SUM.LT.0.) GO TO 90                                            2894
      DO 100 MX=1,14                                                     2895
      IND=(MX-1)*36                                                      2896
      IA=DMN(IND+1)                                                      2897
      JA=DMN(IND+2)                                                      2898
      IC=IND+ICODE                                                       2899
      IDG=3                                                              2900
      IF (IDIST.EQ.2) IDG=4                                              2901
      DUMVAR(ICODE)=DMN(IC)                                              2902
      DUMVAR(IDIST)=DMN(IND+IDG)                                         2903
      IF (IDIST.EQ.3.AND.IA.GE.KL1.AND.IA.LE.KL2.AND.JA.EQ.KL3) XLF(KL)= 2904
     1DUMVAR(IDIST)                                                      2905
      IF (IDIST.EQ.3.AND.IA.GE.KL1.AND.IA.LE.KL2.AND.JA.EQ.KL3) YLF(KL)= 2906
     1DUMVAR(ICODE)                                                      2907
      IF (IDIST.EQ.3.AND.IA.GE.KL1.AND.IA.LE.KL2.AND.JA.EQ.KL3) KL=KL+1  2908
      IF (IDIST.EQ.3.AND.IA.GE.KL1.AND.IA.LE.KL2.AND.JA.EQ.KL3) PRINT 18 2909
     10, IA,JA,KL,XLF(KL-1),YLF(KL-1)                                    2910
      IF (IDIST.EQ.2.AND.JA.GE.KL3.AND.JA.LE.KL4.AND.IA.EQ.KL1) XLF(KL)= 2911
     1DUMVAR(IDIST)                                                      2912
      IF (IDIST.EQ.2.AND.JA.GE.KL3.AND.JA.LE.KL4.AND.IA.EQ.KL1) YLF(KL)= 2913
     1DUMVAR(ICODE)                                                      2914
      IF (IDIST.EQ.2.AND.JA.GE.KL3.AND.JA.LE.KL4.AND.IA.EQ.KL1) KL=KL+1  2915
      IF (IDIST.EQ.2.AND.JA.GE.KL3.AND.JA.LE.KL4.AND.IA.EQ.KL1) PRINT 18 2916
     10, IA,JA,KL,XLF(KL-1),YLF(KL-1)                                    2917
      IF (IDIST.EQ.3.AND.IA.EQ.KL2.AND.JA.EQ.KL3) GO TO 110              2918
      IF (IDIST.EQ.2.AND.JA.EQ.KL4.AND.IA.EQ.KL1) GO TO 110              2919
  100 CONTINUE                                                           2920
      GO TO 90                                                           2921
  110 CONTINUE                                                           2922
      TZERO=T                                                            2923
      REWIND 14                                                          2924
  120 CALL GRIDS                                                         2925
      IF (T.LT.TZERO) GO TO 120                                          2926
      ICH=KL-2                                                           2927
      NX=MDIM(I)                                                         2928
      CALL LABPLT (ICH,ICODE,IR,JR,NX)                                   2929
      KL=1                                                               2930
      IF (T.GT.TPLTMA) GO TO 130                                         2931
      GO TO 90                                                           2932
  130 CONTINUE                                                           2933
  140 CONTINUE                                                           2934
      IF (INUMM.EQ.1) GO TO 10                                           2935
      CALL PLOT (X,Y,999)                                                2936
      RETURN                                                             2937
C                                                                        2938
C                                                                        2939
  150 FORMAT (10X,100(1H*),/,25X,25H      GRID PLOT           ,7HIVEL = ,  2940
     13X,I3,5X,8HMOVIE = ,3X,I3,5X,6HISC = ,3X,I3,/,10X,100(1H*))        2941
  160 FORMAT (10X,100(1H*),/,25X,25H TEMPORAL DISTRIBUTION   ,/,20X,30H   2942
     1  KL1,KL2,KL3,KL4,ICODE       ,6(2X,I3),/,10X,100(1H*))           2943
```

```
  170 FORMAT (10X,100(1H*),/,25X,25H SPATIAL DISTRIBUTION     ,/,20X,30H
     1  KL1,KL2,KL3,KL4, ICODE, IDIST,6(2X,I3),/,10X,100(1H*))
  180 FORMAT (21H  IA,JA,KL,XLF,YLF    ,3(2X,I3),2(1X,E12.4))
      END
      SUBROUTINE RDPLT
C
C
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C     READS CARD INPUT FOR PLOTTING
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C
      COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH
      COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTDL,TZERO,T
      COMMON/P1/XGRAPH(45),ZGRAPH(225),XVELT(45,225),ZVELT(45,225),
     1SH(45,225),DR(45),DZ(225), NOLIN1(45,225),NOLIN2(45,225),ILOW,
     1IHIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC,
     2DMN(525),XLF(225),YLF(225),IPLOW,IPHIGH,JPLOW,JPHIGH,XPT(50,11),
     3YPT(50,11)
      COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR
     1MIN(10),JRMAX(10),MPODE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG
      COMMON /P3/ ZZ,LI1,LI2,LI3,LI4,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL
     1O,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M
     2OVIE,IDET,IVEL,RPV,ILINE,MZODE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20
     3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM
      DATA IKQ/0/
C
C
      IKQ=IKQ+1
      IF (IKQ.EQ.1) TZ=T
      KL1=0
      KL2=0
      KL3=0
      KL4=0
      ICHECK=0
C     ***********************************************************************
C     IHIST= NUMBER OF TIME HISTORY CARDS
C     RPV=RASTERS/UNIT VELOCITY,CURRENT,ETC.
C     ISPAT=NUMBER OF SPATIAL CARDS
C     IPARAM=NUMBER OF PARAMETERS ON SAME PLOT
C     ILINE=NUMBER OF LINE CARDS (USUSALLY 2)
C     IVEL =0 ,NO VELOCITY VECTORS.........IVEL =1,VELOCITY VECTORS
C     MOVIE=0, NO MOVIE.....MOVIE=1, MOVIE......MOVIE=3, CONTOUR MAP
C     NCODE = 1 (X) = 2 (Z)
C     ISC=-1, SHADING.......ISC = 0 NO SHADING
C     NSHADE = DEGREE OF SHADING (1=DARKEST,10=LIGHTEST)
C     ISYM=0 (NO MIRROR IMAGE), =1 (MIRROR IMAGE ABOUT X - AXIS) =2 (
C     MIRROR IMAGE ABOUT Z - AXIS)
C     IDET=1,JUST GRID WITHOUT AXIA); IDET=3,PUNCHED CARDS OF SHADE/
C     3-D/CONTOUR Z (SH) VALUES; IDET=5, 3-D PERSPECTIVE
C     MDIM=1(X-DIRECTION),2(Z-DIRECTION) IN SPATIAL DISTRIBUTION PLOTS.
C     MCODE AND MZODE ( TIME / SPATIAL DISTRIBUTION VARIABLES ) SELECTED
C     FROM BELOW......TABLE C.1 IN AEDC TR-77-105
C     E1= MINIMUM VALUE FOR SHADING, E2= MAXIMUM VALUE FOR SHADING
C     LI1= VARIABLE TO BE SHADED, LI2= LINEAR(0), LOGARITHMIC(1)
C     LI3 = 1 IF HALF PLOT IS SHADED AND HALF PLOT IS VECTORS
C     NOTE THAT SHADING IMPLIES 3-D PERSPECTIVE AND CONTOUR MAPPING ALSO
C     3 R       8 V      13 MACH  18 TZZ   23 VISC  28 GAMMA 33 PHI
C     5 DR     10 E      15 M     20 TRZ   25 BZ    30   -   35 COND(T)
C     6 DZ      11 INT   16 BO    21 TIME  26 JR    31 TEMP  36 VORT
C     7 U      12 C      17 TRR   22 DT    27 JZ    32 CV
C     ***********************************************************************
      WRITE (6,170) (TITLE(I),I=1,15)
      READ 180, MOVIE,IHIST,ISPAT,IPARAM,ILINE,ISC,IDET,ISYM,IVEL,RPV,IP
```

```
     1ART                                                                    3008
      PRINT 190, MOVIE,IHIST,ISPAT,IPARAM,ILINE,ISC,IDET,ISYM,IVEL,RPV,I     3009
     1PART                                                                   3010
      READ 200, ILOW,IHIGH,JLOW,JHIGH,L1,L2,L3,L4,JPDEL,KPDEL               3011
      IF (JPDEL.EQ.0) JPDEL=1                                               3012
      IF (KPDEL.EQ.0) KPDEL=1                                               3013
      IF (L1.EQ.0) PRINT 220, ILOW,IHIGH,JLOW,JHIGH,JPDEL,KPDEL             3014
      IF (L1.NE.0) PRINT 210, ILOW,IHIGH,JLOW,JHIGH,L1,L2,L3,L4             3015
      IF (L1.EQ.0) L1=ILOW                                                  3016
      IF (L2.EQ.0) L2=IHIGH                                                 3017
      IF (L3.EQ.0) L3=JLOW                                                  3018
      IF (L4.EQ.0) L4=JHIGH                                                 3019
      DO 10 K1=1,IHIGH                                                      3020
      DO 10 J1=1,JHIGH                                                      3021
      SH(K1,J1)=0.                                                          3022
      NOLIN1(K1,J1)=0                                                       3023
      NOLIN2(K1,J1)=0                                                       3024
   10 CONTINUE                                                              3025
      READ 230, ZLOW,ZHIGH,XLOW,XHIGH                                       3026
      PRINT 240, ZLOW,ZHIGH,XLOW,XHIGH                                      3027
      IF (IPART.EQ.0) GO TO 20                                              3028
      READ (5,140) IPLOW,IPHIGH,JPLOW,JPHIGH,NPTS                           3029
      WRITE (6,150) IPLOW,IPHIGH,JPLOW,JPHIGH,NPTS                          3030
   20 CONTINUE                                                              3031
C     ***********************************************************************3032
C     VECTORS                                                               3033
C     ***********************************************************************3034
      IF (IVEL.EQ.0) GO TO 30                                               3035
      READ 250, IVX,IVZ,KLOG                                                3036
      PRINT 260, IVX,IVZ,KLOG                                               3037
   30 CONTINUE                                                              3038
C     ***********************************************************************3039
C     TIME HISTORY CARDS                                                    3040
C     ***********************************************************************3041
      IF (IHIST.EQ.0) GO TO 50                                              3042
      PRINT 270                                                             3043
      DO 40 I=1,IHIST                                                       3044
      READ 290, IHMIN(I),IHMAX(I),JHMIN(I),JHMAX(I),MCODE(I),MFRAME(I,1)    3045
      PRINT 280, IHMIN(I),IHMAX(I),JHMIN(I),JHMAX(I),MCODE(I),MFRAME(I,1    3046
     1)                                                                     3047
      MCODE(I)=MCODE(I)                                                     3048
   40 CONTINUE                                                              3049
C     ***********************************************************************3050
C     ELIMINATING LINES IN GRIDS                                            3051
C     ***********************************************************************3052
   50 IF (ILINE.EQ.0) GO TO 80                                              3053
      PRINT 300                                                             3054
      DO 70 N=1,ILINE                                                       3055
      READ 290, ISMIN,ISMAX,JSMIN,JSMAX,NCODE                               3056
      PRINT 310, ISMIN,ISMAX,JSMIN,JSMAX,NCODE                              3057
      DO 60 I=ILOW,IHIGH                                                    3058
      DO 60 J=JLOW,JHIGH                                                    3059
      IF (NCODE.EQ.1.AND.I.GE.ISMIN.AND.I.LE.ISMAX.AND.J.GE.JSMIN.AND.J.    3060
     1LE.JSMAX) NOLIN1(I,J)=1                                               3061
      IF (NCODE.EQ.2.AND.I.GE.ISMIN.AND.I.LE.ISMAX.AND.J.GE.JSMIN.AND.J.    3062
     1LE.JSMAX) NOLIN2(I,J)=1                                               3063
   60 CONTINUE                                                              3064
   70 CONTINUE                                                              3065
C     ***********************************************************************3066
C     SPATIAL DISTRIBUTION CARDS                                            3067
C     ***********************************************************************3068
   80 IF (ISPAT.EQ.0) GO TO 100                                             3069
      PRINT 320                                                             3070
      DO 90 N=1,ISPAT                                                       3071
```

```
      READ 340, IZMIN(N),IZMAX(N),JZMIN(N),JZMAX(N),MZODE(N),MFRAME(N,2)
      PRINT 330, IZMIN(N),IZMAX(N),JZMIN(N),JZMAX(N),MZODE(N),MFRAME(N,2
     1)
      MDIM(N)=2
      IF (IZMIN(N).NE.IZMAX(N)) MDIM(N)=1
      MZODE(N)=MZODE(N)
   90 CONTINUE
C     ******************************************************************
C     SHADING ZONES
C     ******************************************************************
  100 CONTINUE
      IF (ISC.EQ.-1) READ 350, E1,E2,LI1,LI2,LI3
      IF (ISC.EQ.-1) PRINT 360, E1,E2,LI1,LI2,LI3
C     ******************************************************************
C     PARAMETRIC PLOTS
C     ******************************************************************
      IF (IPARAM.EQ.0) GO TO 120
      DO 110 N=1,IPARAM
      READ 290, IRMIN(N),IRMAX(N),JRMIN(N),JRMAX(N),MPODE(N)
      PRINT 160, IRMIN(N),IRMAX(N),JRMIN(N),JRMAX(N),MPODE(N)
  110 CONTINUE
  120 READ 370, TPLTMI,TPLTMA,TPLTDE,TPLTDL,INUMM
      IF (TPLTMA.GT.TZ) TPLTMA=0.99999*TZ
      IF (TPLTDL.GT.TZ) TPLTDL=0.99999*TZ
      IF (TPLTDE.GT.TZ) TPLTDE=0.99999*TZ
      T=0.
C     ******************************************************************
C     PLOT TIME STEPS
C     ******************************************************************
C     TZERO=-TPLTDE
      TZERO=0.
      IF (TPLTDL.NE.0.) PRINT 380, TPLTMI,TPLTMA,TPLTDE,TPLTDL
      IF (TPLTDL.NE.0.) GO TO 130
      PRINT 390, TPLTMI,TPLTMA,TPLTDE
  130 RETURN
C
C
  140 FORMAT (6(I5))
  150 FORMAT (3X,5HIPLOW,2X,6HIPHIGH,3X,5HJPLOW,2X,6HJPHIGH,4X,4HNPTS,/,
     14X,I3,6X,I3,5X,I3,6X,I3,4X,I3)
  160 FORMAT (32H   IRMIN IRMAX JRMIN JRMAX MPODE,/,5(3X,I3))
  170 FORMAT (1H1,///,15A4)
  180 FORMAT (9I5,5X,E10.4,I5)
  190 FORMAT (78H   MOVIE   IHIST   ISPAT   IPARAM  ILINE    ISC      IDE
     1T    ISYM    IVEL   RPV,10H    IPART ,/,2X,I3,8(5X,I3),2X,E10.4,2X
     2,I3)
  200 FORMAT (10I5)
  210 FORMAT (55H   ILOW   IHIGH    JLOW   JHIGH    L1    L2    L3    L4
     1,/,2X,8(I3,5X))
  220 FORMAT (47H   ILOW    IHIGH    JLOW   JHIGH  JPDEL  KPDEL ,/,2X,6(
     1I3,5X))
  230 FORMAT (4F10.4)
  240 FORMAT (45H   ZLOW         ZHIGH       XLOW        XHIGH,/,4(2X,E1
     10.4))
  250 FORMAT (3I5)
  260 FORMAT (19H   IVX   IVZ   KLOG,/,3(3X,I3))
  270 FORMAT (39H   IHMIN IHMAX JHMIN JHMAX MCODE MFRAME)
  280 FORMAT (6(3X,I3))
  290 FORMAT (6I5)
  300 FORMAT (32H   ISMIN ISMAX JSMIN JSMAX NCODE)
  310 FORMAT (5(3X,I3))
  320 FORMAT (39H   IZMIN IZMAX JZMIN JZMAX MZODE MFRAME)
  330 FORMAT (6(3X,I3))
  340 FORMAT (6I5)
```

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  350 FORMAT (2E10.4,3(5X,I5))                                                    3136
  360 FORMAT (60H              E1                    E2              LI1          3137
     1      ,19H LI2              LI3,/,5X,E15.5,5X,E15.5,3(5X,I5,5X))           3138
  370 FORMAT (4F10.4,39X,I1)                                                      3139
  380 FORMAT (46H    TPLTMI       TPLTMA       TPLTDE       TPLTDL ,/,4(2X,E     3140
     110.4),///)                                                                  3141
  390 FORMAT (36H    TPLTMI       TLPTMA       TPLTDE    ,/,3(2X,E10.4),///)    3142
      END                                                                         3143
      SUBROUTINE GRIDS                                                        3144
C                                                                             3145
C                                                                             3146
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 3147
C     DRAWS GRID, INITIATES SHADING,MAPPING, 3-D AND TRACER PLOTS             3148
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 3149
C                                                                             3150
C                                                                             3151
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                                3152
      COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH           3153
      COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTDL,TZERO,T                       3154
      COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),IDYM(4),IAXI,IOBQ       3155
      COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX       3156
      COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF                 3157
      COMMON/CGRID/R(45),RD(45),Z(225),FR(45),FZ(225),XF(45),ZMIN,RMIN,D      3158
     1ZO,DRO,IGRAPH(225),NBOUND                                               3159
      COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM      3160
     1,NVECT,NPDIM                                                            3161
      COMMON /MOVE/ XX(4),YY(4)                                               3162
      COMMON/P1/XGRAPH(45),ZGRAPH(225),XVELT(45,225),ZVELT(45,225),           3163
     1SH(45,225),DR(45),DZ(225),  NOLIN1(45,225),NOLIN2(45,225),ILOW,         3164
     1IHIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC,      3165
     2DMN(525),XLF(225),YLF(225),IPLOW,IPHIGH,JPLOW,JPHIGH,XPT(50,11),        3166
     3YPT(50,11)                                                              3167
      COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR      3168
     1MIN(10),JRMAX(10),MPODE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG        3169
      COMMON /P3/ ZZ,LI1,LI2,LI3,LI4,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL      3170
     1O,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M      3171
     2OVIE,IDET,IVEL,RPV,ILINE,MZODE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20      3172
     3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM                       3173
      DIMENSION XGEQ(45),ZGEQ(225),XP(2,2),YP(2,2),TP(2,2),LL(200),           3174
     1S(200),TLABEL(102),INSND(225),IZZ(225)                                  3175
      REAL*8 R,RD                                                             3176
      EQUIVALENCE (XGRAPH,XGEQ), (ZGRAPH,ZGEQ)                                3177
      DATA LL/200*0/                                                          3178
      DATA TLABEL/4H  R-,4HRADI,4HAL  ,4H  Z-,4HAXIA,4HL   ,4H  DE,4HLTA      3179
     1-,4HR   ,4H  DE,4HLTA-,4HZ   ,4H VEL,4HOCIT,4HY-Z ,4H VEL,4HOCIT,4      3180
     2HY-R ,4H  PR,4HESSU,4HRE  ,4HTOTA,4HL EN,4HERGY,4H INT,4HERNA,4HL       3181
     3EN,4H SPE,4HED S,4HOUND,4H  MA,4HCH N,4HO   ,4H   D,4HENSI,4HTY  ,      3182
     44H    ,4HMASS,4H    ,4H  MA,4HGN I,4HND O,4H    ,4H TRR,4H    ,4H      3183
     5   ,4H TZZ,4H    ,4H    ,4H TOO,4H    ,4H    ,4H TRZ,4H    ,4H        3184
     6,4H ER ,4H    ,4H    ,4H EZ ,4H    ,4H  VI,4HSCOS,4HITY ,4HMAGN,4H      3185
     7 FLD,4H R  ,4HMAGN,4H FLD,4H Z  ,4H CUR,4HRENT,4H-R  ,4H CUR,4HREN      3186
     8T,4H-Z  ,4H   C,4HP/CV,4H    ,4H CON,4HD EL,4HECTR,4H    ,4H    ,4      3187
     9H    ,4HTEMP,4HERAT,4HURE ,4HSP H,4HEAT ,4HVOL ,4H POT,4HENTI,4HAL      3188
     $  ,4HHALL,4H PAR,4HMTER,4H CON,4HD TH,4HERML,4H VOR,4HTICI,4HTY  /      3189
C                                                                             3190
C                                                                             3191
      XX(3)=0.                                                                3192
      XX(4)=1.                                                                3193
      YY(3)=0.                                                                3194
      YY(4)=1.                                                                3195
      IFRT=1                                                                  3196
      IBACK=JHIGH                                                             3197
      DO 10 KS=1,JHIGH                                                        3198
   10 INSND(KS)=-1                                                            3199
```

```
      SHDBND=4                                                                  3200
      IF (MFR.EQ.1) RETURN                                                      3201
      IF (IPOT.EQ.0) GO TO 20                                                   3202
      ISP=SPINSL+SPACE                                                          3203
      JIP=0                                                                     3204
      ICND=1                                                                    3205
      IELECT=SPACE                                                              3206
   20 CONTINUE                                                                  3207
      LIMIT=0                                                                   3208
C     ************************************************************************* 3209
C     READING FROM UNIT 14                                                      3210
C     ************************************************************************* 3211
   30 READ (14) (DMN(KX),KX=1,504),T,NCYCLE,DT                                  3212
      DO 60 L=1,14                                                              3213
      IF (LIMIT.EQ.1) GO TO 60                                                  3214
      LA=(L-1)*36                                                               3215
      II=DMN(LA+1)                                                              3216
      JJ=DMN(LA+2)                                                              3217
      IF (JJ.EQ.1) XGRAPH(II)=DMN(LA+3)                                         3218
      ZGRAPH(JJ)=DMN(LA+4)                                                      3219
      XVELT(II,JJ)=DMN(LA+8)                                                    3220
      ZVELT(II,JJ)=DMN(LA+7)                                                    3221
      IF (IVEL.NE.0) XVELT(II,JJ)=DMN(LA+IVX)                                   3222
      IF (IVEL.NE.0) ZVELT(II,JJ)=DMN(LA+IVZ)                                   3223
      DO 40 KR=3,36                                                             3224
      LAF=LA+KR                                                                 3225
   40 DUMVAR(KR)=DMN(LAF)                                                       3226
      IF (DUMVAR(30).EQ.2.) NOLIN1(II,JJ)=2                                     3227
      IF (DUMVAR(30).EQ.2.) NOLIN2(II,JJ)=2                                     3228
      IF (IPOT.EQ.0) GO TO 50                                                   3229
      IF (JJ.LT.JPLMIN.OR.JJ.GT.JPLMAX) GO TO 50                                3230
      IPL1=KP2+1-IGRAPH(JJ)                                                     3231
      IPL2=IGRAPH(JJ)                                                           3232
      IF (II.NE.IPL2) GO TO 50                                                  3233
      JIP=JIP+1                                                                 3234
      IF (JIP.LE.IELECT) INSND(JJ)=ICND                                         3235
      IF (JIP.GT.IELECT) INSND(JJ)=0                                            3236
      IF (JIP.EQ.ISP) JIP=0                                                     3237
      IF (JIP.EQ.0) ICND=ICND+1                                                 3238
   50 CONTINUE                                                                  3239
      DR(II)=DUMVAR(5)                                                          3240
      DZ(JJ)=DUMVAR(6)                                                          3241
      IF (II.EQ.L2.AND.JJ.EQ.L4) LIMIT=1                                        3242
C     ************************************************************************* 3243
C     DETERMINING SHADE, CONTOUR OR 3-D VARIBLE VALUE (SH)                      3244
C     ************************************************************************* 3245
      IF (ISC.NE.-1) GO TO 60                                                   3246
      IF (NOLIN1(II,JJ).GT.2) GO TO 60                                          3247
      IF (LI2.EQ.0) DELTA=(E2-E1)/10.                                           3248
      IF (LI2.EQ.1) DELTA=(ALOG10(E2)-ALOG10(E1))/10.                           3249
      SH(II,JJ)=0.                                                              3250
      IF (LI1.NE.33) DUMVAR(LI1)=ABS(DUMVAR(LI1))                               3251
      IF (LI2.EQ.1.AND.DUMVAR(LI1).LE.1..AND.LI1.NE.33) GO TO 60                3252
      IF (LI2.EQ.0) SH(II,JJ)=(DUMVAR(LI1)-E1)/DELTA                            3253
      IF (LI2.EQ.1) SH(II,JJ)=(ALOG10(DUMVAR(LI1))-ALOG10(E1))/DELTA            3254
      IF (SH(II,JJ).LT.-2.5) SH(II,JJ)=-2.5                                     3255
      IF (SH(II,JJ).GT.12.5) SH(II,JJ)=12.5                                     3256
   60 CONTINUE                                                                  3257
C     ************************************************************************* 3258
C     CONTOUR LIMITS                                                            3259
C     ************************************************************************* 3260
      IF (LIMIT.EQ.0) GO TO 30                                                  3261
      IF (ISC.NE.-1) GO TO 80                                                   3262
      S(1)=E1                                                                   3263
```

```
      DO 70 KM=2,200                                                    3264
      S(KM)=S(KM-1)+DELTA/4.                                            3265
   70 CONTINUE                                                          3266
   80 CONTINUE                                                          3267
      ITOP=0                                                            3268
      IHALF=L2/2                                                        3269
      IF (XGRAPH(IHALF).GT.0.) ITOP=1                                   3270
      IF (T.LT.TPLTMI) RETURN                                           3271
      SUM=T-TPLTDE-TZERO                                                3272
      IF (IHIST.LT.1.AND.ISPAT.LT.1.AND.SUM.LT.0.) RETURN               3273
      IF (IHIST.LT.1.AND.ISPAT.LT.1) TZERO=T                            3274
      IF (IHIST.GE.1.AND.T.LT.TZERO) RETURN                             3275
      IF (ISPAT.GE.1.AND.T.LT.TZERO) RETURN                             3276
      IBACK=0                                                           3277
      IFRT=0                                                            3278
      IF (IOBQ.EQ.0) GO TO 170                                          3279
C     ******************************************************************3280
C     DEFINING SOLID BOUNDARY AND ELECTRODES FOR GRID IDENTIDICATION    3281
C     ******************************************************************3282
      DO 120 J5=JLOW,JHIGH                                              3283
      K5=IGRAPH(J5)                                                     3284
      KOBL=KP2+1-IGRAPH(J5)                                             3285
      IF (K5.GT.L2) GO TO 120                                           3286
      IF (K5.LE.L2.AND.NVECT.EQ.2) NOLIN1(KOBL,J5)=5                    3287
      IF (K5.LE.L2) NOLIN1(K5,J5)=5                                     3288
      IF (K5.EQ.L2) GO TO 100                                           3289
      KIX=K5+1                                                          3290
      DO 90 KX=KIX,IHIGH                                                3291
      LX=KP2+1-KX                                                       3292
      IF (J5.EQ.JLOW.OR.J5.EQ.JHIGH) GO TO 90                           3293
      IF (NOLIN1(KX,J5+1).EQ.1.OR.NOLIN1(KX,J5-1).EQ.1) NOLIN1(KX,J5)=5 3294
      IF (NOLIN1(KX,J5+1).EQ.1.AND.NVECT.EQ.2) NOLIN1(LX,J5)=5          3295
      IF (NOLIN1(KX,J5-1).EQ.1.AND.NVECT.EQ.2) NOLIN1(LX,J5)=5          3296
   90 CONTINUE                                                          3297
  100 CONTINUE                                                          3298
      IF (IPOT.EQ.0) GO TO 110                                          3299
      IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSNO(J5).EQ.0) NOLIN1(K5,J5 3300
     1)=3                                                               3301
      IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSNO(J5).EQ.0) NOLIN1(K5,J5 3302
     1)=5                                                               3303
      IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSNO(J5).EQ.0) NOLIN1(K5,J5 3304
     1)=5                                                               3305
      IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSNO(J5).NE.0) NOLIN1(K5,J5 3306
     1)=4                                                               3307
      IF (NVECT.NE.2) GO TO 110                                         3308
      IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSNO(J5).EQ.0) NOLIN1(KOBL, 3309
     1J5)=3                                                             3310
      IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSNO(J5).EQ.0) NOLIN1(KOBL, 3311
     1J5)=5                                                             3312
      IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSNO(J5).EQ.0) NOLIN1(KOBL, 3313
     1J5)=5                                                             3314
      IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSNO(J5).NE.0) NOLIN1(KOBL, 3315
     1J5)=4                                                             3316
  110 CONTINUE                                                          3317
      IF (K5.LE.L2) IBACK=J5                                            3318
      IF (K5.LE.L2.AND.IFRT.EQ.0) IFRT=J5                               3319
      IF (IOBQ.NE.0.AND.NOLIN1(L2,J5).GT.1.AND.ISYM.NE.2) NOLIN1(L2,J5)= 3320
     15                                                                 3321
      IF (IOBQ.NE.0.AND.NOLIN1(L2,J5).GT.1.AND.ISYM.EQ.2.AND.ITOP.EQ.1) 3322
     1NOLIN1(L2,J5)=5                                                   3323
      IF (IOBQ.NE.0.AND.NVECT.EQ.2) NOLIN1(1,J5)=5                      3324
  120 CONTINUE                                                          3325
      MM=IGRAPH(IFRT)                                                   3326
      DO 130 M6=MM,IHIGH                                                3327
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  130 NOLIN1(M6,IFRT)=5                                                    3328
      NN=IGRAPH(IBACK)                                                     3329
      DO 140 N6=NN,IHIGH                                                   3330
  140 NOLIN1(N6,IBACK)=5                                                   3331
      IF (NVECT.NE.2) GO TO 170                                            3332
      KFRT=KP2+1-IGRAPH(IFRT)                                              3333
      KBCK=KP2+1-IGRAPH(IBACK)                                             3334
      KLO=KP2+1-IHIGH                                                      3335
      DO 150 M6=KLO,KFRT                                                   3336
  150 NOLIN1(M6,IFRT)=5                                                    3337
      DO 160 N6=KLO,KBCK                                                   3338
  160 NOLIN1(N6,IBACK)=5                                                   3339
  170 CONTINUE                                                             3340
      IF (NCYCLE.GT.1) GO TO 180                                           3341
      IF (MOVIE.LT.5) GO TO 180                                            3342
      CALL FRAMEV (3)                                                      3343
      IDUM=0                                                               3344
      CALL SYMBOL (2.,5.,.30,TITLE,0.,30)                                  3345
  180 CONTINUE                                                             3346
      PRINT 550, NCYCLE,T,DT                                               3347
      LSYM=-1                                                              3348
C     ***********************************************************************3349
C     PLOTTING GRIDS                                                       3350
C     ***********************************************************************3351
      CALL FRAMEV (3)                                                      3352
C     ***********************************************************************3353
C     MARGIN LINES AND LABELLING                                           3354
C     ***********************************************************************3355
      CALL NXVOSB (1,ZLOW,ZHIGH,IIII)                                      3356
      CALL NXVOSB (2,XLOW,XHIGH,IIII)                                      3357
      IF (IDET.EQ.1) GO TO 220                                             3358
      CALL CHSIZV (2,2)                                                    3359
      TUB=T*10.**3                                                         3360
      DO 190 KS=1,5                                                        3361
      IF (IHIST.GT.0.OR.ISPAT.GT.0) GO TO 210                              3362
      CALL CHSIZV (3,3)                                                    3363
      CALL SYMBOL (3.8,1.3,.10,11HTIME (MSEC),0.,11)                       3364
      DO 185 KW=1,15                                                       3365
      XCD=2.+KW*0.70                                                       3366
  185 CALL SYMBOL(XCD,9.3,.2,TITLE(KW),0.,4)                               3367
      CALL NUMBER (6.5,1.3,.2,TUB,0.,4)                                    3368
      CALL SYMBOL (4.8,1.0,.1,5HCYCLE,0.,5)                                3369
      CYCLE=NCYCLE                                                         3370
      CALL NUMBER (5.8,1.0,.1,CYCLE,0.,-1)                                 3371
      CALL CHSIZV (2,2)                                                    3372
  190 CONTINUE                                                             3373
      WRITE (6,540) TUB                                                    3374
      CALL SYMBOL (4.5,0.22,.12,12HZ-AXIAL (CM),0.,12)                     3375
      CALL SYMBOL (.45,4.5,.12,12HX-RADIAL(CM),90.,12)                     3376
      IF (LI1.EQ.0) GO TO 200                                              3377
      CLI1=LI1                                                             3378
      JCODE=3*(LI1-3)+1                                                    3379
      CALL SYMBOL (1.75,9.0,.12,TLABEL(JCODE),0.,4)                        3380
      CALL SYMBOL (2.23,9.0,.12,TLABEL(JCODE+1),0.,4)                      3381
      CALL SYMBOL (2.71,9.0,.12,TLABEL(JCODE+2),0.,4)                      3382
      F1=E1                                                                3383
      F2=E2                                                                3384
      IF (LI1.EQ.33.AND.IPTSF.EQ.2) F1=F1*10.**(-8)                        3385
      IF (LI1.EQ.33.AND.IPTSF.EQ.2) F2=F2*10.**(-8)                        3386
      IF (LI2.EQ.1) F1=ALOG10(E1)                                          3387
      IF (LI2.EQ.1) F2=ALOG10(E2)                                          3388
      CALL NUMBER (1.5,8.75,.12,F1,0.,3)                                   3389
      CALL SYMBOL (2.3,8.75,.12,2HTO,0.,2)                                 3390
      CALL NUMBER (3.1,8.75,.12,F2,0.,3)                                   3391
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      IF (LI2.EQ.0) CALL SYMBOL (8.0,9.00,.12,10H  LINEAR  ,0.,10)          3392
      IF (LI2.NE.0) CALL SYMBOL (8.00,9.0,.12,10H LOGARITHM,0.,10)         3393
  200 CONTINUE                                                             3394
      DX=(ZHIGH-ZLOW)/10.                                                  3395
      DY=(XHIGH-XLOW)/10.                                                  3396
      LX=2                                                                 3397
      LY=1                                                                 3398
  210 CONTINUE                                                             3399
C     ********************************************************************3400
C     MIRROR IMAGE                                                         3401
C     ********************************************************************3402
  220 LSYM=LSYM+1                                                          3403
      IF (LSYM.EQ.0) GO TO 250                                             3404
      DO 230 JEK=JLOW,JHIGH                                                3405
      IF (ISYM.EQ.1) ZGEQ(JEK)=-ZGRAPH(JEK)                                3406
  230 CONTINUE                                                             3407
      DO 240 IEK=ILOW,IHIGH                                                3408
      IF (ISYM.EQ.2) XGEQ(IEK)=-XGRAPH(IEK)                                3409
  240 CONTINUE                                                             3410
  250 CONTINUE                                                             3411
      DO 260 KLLL=1,IHIGH                                                  3412
      WRITE (6,470) (NOLIN1(KLLL,LJJJ),LJJJ=1,JHIGH)                       3413
  260 CONTINUE                                                             3414
C     ********************************************************************3415
C     HORIZONTAL GRIDS                                                     3416
C     ********************************************************************3417
      ISEN=1                                                               3418
      IF (LSYM.EQ.1) ISEN=-1                                               3419
      DO 280 LJ=JLOW,JHIGH                                                 3420
      IPP1=KP2+1-IGRAPH(LJ)                                                3421
      DO 280 LI=ILOW,IHIGH                                                 3422
      IF (NOLIN1(LI,LJ).EQ.1) GO TO 280                                    3423
      ZG1=ZGRAPH(LJ)+DZ(LJ)/2.                                             3424
      XG1=XGRAPH(LI)-DR(LI)/2.*ISEN                                        3425
      ZG2=ZGRAPH(LJ)-DZ(LJ)/2.                                             3426
      XG2=XGRAPH(LI)+DR(LI)/2.*ISEN                                        3427
      CALL NXVOSB (3,ZG1,T,M1)                                             3428
      CALL NXVOSB (4,XG1,T,M2)                                             3429
      CALL NXVOSB (3,ZG2,T,M3)                                             3430
      CALL NXVOSB (4,XG2,T,M4)                                             3431
      IF (NVECT.EQ.2.AND.LI.EQ.IPP1) CALL LINEV (M1,M4,M3,M4)              3432
      IF (LI.LT.IHIGH) GO TO 270                                           3433
      CALL LINEV (M1,M4,M3,M4)                                             3434
  270 CALL LINEV (M1,M2,M3,M2)                                             3435
  280 CONTINUE                                                             3436
C     ********************************************************************3437
C     VERTICAL GRID LINES                                                  3438
C     ********************************************************************3439
      DO 310 LJ=JLOW,JHIGH                                                 3440
      DO 310 LI=ILOW,IHIGH                                                 3441
      CALL NXVOSB (3,ZGRAPH(LJ),T,MX1)                                     3442
      CALL NXVOSB (4,XGRAPH(LI),T,MY1)                                     3443
      IF (NOLIN2(LI,LJ).EQ.1) GO TO 290                                    3444
      XG1=XGRAPH(LI)-DR(LI)/2.*ISEN                                        3445
      ZG1=ZGRAPH(LJ)-DZ(LJ)/2.                                             3446
      XG2=XGRAPH(LI)+DR(LI)/2.*ISEN                                        3447
      ZG2=ZGRAPH(LJ)+DZ(LJ)/2.                                             3448
      CALL NXVOSB (3,ZG1,T,M1)                                             3449
      CALL NXVOSB (3,ZG2,T,M3)                                             3450
      CALL NXVOSB (4,XG1,T,M2)                                             3451
      CALL NXVOSB (4,XG2,T,M4)                                             3452
      IF (LJ.EQ.JHIGH) CALL LINEV (M3,M2,M3,M4)                            3453
      IPIC=0                                                               3454
      IF (LJ.LT.JHIGH) IPIC=1                                              3455
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      IF (IPIC.EQ.1.AND.IGRAPH(LJ).NE.IGRAPH(LJ+1)) CALL LINEV (M3,M2,M3   3456
     1,M4)                                                                 3457
      CALL LINEV (M1,M2,M1,M4)                                             3458
  290 CONTINUE                                                             3459
C     ***********************************************************************3460
C     VECTORS                                                              3461
C     ***********************************************************************3462
      IF (ISC.EQ.-1.AND.LI3.EQ.1.AND.LSYM.EQ.0) GO TO 300                  3463
      IF (IVEL.NE.1) GO TO 300                                             3464
      IF (MOD(LI,KPDEL).NE.0.OR.MOD(LJ,JPDEL).NE.0) GO TO 300              3465
      IF (NOLIN1(LI,LJ).GT.1) GO TO 300                                    3466
      ZZ1=1.                                                               3467
      ZZ2=1.                                                               3468
      IF (LSYM.EQ.1.AND.ISYM.EQ.1) ZZ1=-1.                                 3469
      IF (LSYM.EQ.1.AND.ISYM.EQ.2) ZZ2=-1.                                 3470
      IF (LSYM.EQ.1.AND.XGRAPH(LI).EQ.0.) GO TO 300                        3471
      ZCOMP=ZVELT(LI,LJ)*RPV*ZZ1                                           3472
      XCOMP=XVELT(LI,LJ)*RPV*ZZ2                                           3473
      IF (KLOG.NE.0) XCOMP=ALOG10(XVELT(LI,LJ))*RPV*ZZ2                    3474
      IF (KLOG.NE.0) ZCOMP=ALOG10(ZVELT(LI,LJ))*RPV*ZZ1                    3475
      SUM=ABS(ZCOMP)+ABS(XCOMP)                                            3476
      IF (SUM.LT.1.) GO TO 300                                             3477
      IXC=XCOMP                                                            3478
      IZC=ZCOMP                                                            3479
      IZC=MX1-IZC                                                          3480
      IXC=MY1-IXC                                                          3481
      CALL LINEV (IZC,IXC,MX1,MY1)                                         3482
      CALL ARROW (MX1,MY1,M1,M2,XCOMP,ZCOMP)                               3483
  300 CONTINUE                                                             3484
  310 CONTINUE                                                             3485
C     ***********************************************************************3486
C     CONTOUR MAPPING AND SHADING                                          3487
C     ***********************************************************************3488
      DO 390 LJ=JLOW,JHIGH                                                 3489
      ISW=-1                                                               3490
      DO 390 LI=ILOW,IHIGH                                                 3491
      ISW=-ISW                                                             3492
      ZG1=ZGRAPH(LJ)-DZ(LJ)/2.                                             3493
      XG1=XGRAPH(LI)-DR(LI)/2.*ISEN                                        3494
      ZG2=ZGRAPH(LJ)+DZ(LJ)/2.                                             3495
      XG2=XGRAPH(LI)+DR(LI)/2.*ISEN                                        3496
      IUP=2*NOLIN1(LI,LJ)-1                                                3497
      CALL NXVOSB (3,ZG1,T,M1)                                             3498
      CALL NXVOSB (4,XG1,T,M2)                                             3499
      CALL NXVOSB (3,ZG2,T,M3)                                             3500
      CALL NXVOSB (4,XG2,T,M4)                                             3501
      IF (ISC.NE.-1) GO TO 320                                             3502
C     ***********************************************************************3503
C     COMPUTING X,Y,Z VALUES OF CONTOUR MAP..... CELL BE CELL              3504
C     ***********************************************************************3505
      IF (MOVIE.EQ.0.AND.LI3.EQ.0) GO TO 320                               3506
      IF (MOVIE.EQ.0.AND.LSYM.EQ.1) GO TO 320                              3507
      IF (MOVIE.EQ.3.AND.LI3.NE.0.AND.LSYM.EQ.1) GO TO 320                 3508
      IF (NOLIN1(LI,LJ).GT.1) GO TO 320                                    3509
      XP(1,1)=M1/102.3                                                     3510
      XP(1,2)=M1/102.3                                                     3511
      XP(2,1)=M3/102.3                                                     3512
      XP(2,2)=M3/102.3                                                     3513
      YP(1,1)=M2/102.3                                                     3514
      YP(2,1)=M2/102.3                                                     3515
      YP(1,2)=M4/102.3                                                     3516
      YP(2,2)=M4/102.3                                                     3517
      I=1                                                                  3518
      J=1                                                                  3519
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      K=1                                                                3520
      L=1                                                                3521
      IF (LI.EQ.ILOW) I=0                                                3522
      IF (LI.EQ.IHIGH) K=0                                               3523
      IF (LJ.EQ.JLOW) J=0                                                3524
      IF (LJ.EQ.JHIGH) L=0                                               3525
      TP(1,1)=(SH(LI,LJ)+SH(LI-I,LJ)+SH(LI-I,LJ-J)+SH(LI,LJ-J))/4.*DELTA 3526
     1+E1                                                                3527
      TP(1,2)=(SH(LI,LJ)+SH(LI+K,LJ)+SH(LI+K,LJ-J)+SH(LI,LJ-J))/4.*DELTA 3528
     1+E1                                                                3529
      TP(2,1)=(SH(LI-I,LJ)+SH(LI-I,LJ+L)+SH(LI,LJ)+SH(LI,LJ+L))/4.*DELTA 3530
     1+E1                                                                3531
      TP(2,2)=(SH(LI,LJ)+SH(LI,LJ+L)+SH(LI+K,LJ)+SH(LI+K,LJ+L))/4.*DELTA 3532
     1+E1                                                                3533
      CALL LEVEL (TP,XP,YP,2,2,S,LL,200)                                 3534
  320 CONTINUE                                                           3535
C     ********************************************************************3536
C     DRAWING CELL DIAGONALS                                             3537
C     ********************************************************************3538
      IF (NOLIN1(LI,LJ).LT.2) GO TO 340                                  3539
      IF (NOLIN1(LI,LJ).EQ.3.OR.NOLIN1(LI,LJ).EQ.4) GO TO 340            3540
      DO 330 IBD=1,IUP                                                   3541
      IF (IHIST.NE.0.OR.ISPAT.NE.0) ISW=0                                3542
      IF (ISW.EQ.-1.OR.NOLIN1(LI,LJ).EQ.5) CALL LINEV (M1,M2,M3,M4)      3543
      IF (ISW.EQ.+1.OR.NOLIN1(LI,LJ).EQ.5) CALL LINEV (M3,M2,M1,M4)      3544
  330 CONTINUE                                                           3545
  340 CONTINUE                                                           3546
      IF (IPOT.EQ.0) GO TO 380                                           3547
      IF (NOLIN1(LI,LJ).NE.4) GO TO 380                                  3548
C     ********************************************************************3549
C     NUMBERING ELECTRODE-PAIRS                                          3550
C     ********************************************************************3551
      PNUMB=INSND(LJ)                                                    3552
  350 IF (PNUMB.LT.10.) GO TO 360                                        3553
      PNUMB=PNUMB-10.                                                    3554
      GO TO 350                                                          3555
  360 CONTINUE                                                           3556
      CM1=M2                                                             3557
      CM3=M4                                                             3558
      CHAR=(CM3-CM1)/160.                                                3559
      CHAR=ABS(CHAR)                                                     3560
      MN1=M1+(M3-M1)/10                                                  3561
      MN2=M2+(M4-M2)/10                                                  3562
      MN4=M4+(M2-M4)/10                                                  3563
      XM1=MN1                                                            3564
      XM2=MN2                                                            3565
      IF (LSYM.EQ.1) XM2=MN4                                             3566
      XM1=XM1/102.3+0.20*CHAR                                            3567
      XM2=XM2/102.3+0.12*CHAR                                            3568
      DO 370 MIS=1,6                                                     3569
      IF (NOLIN1(LI,LJ).EQ.4) CALL NUMBER (XM1,XM2,CHAR,PNUMB,0.,-1)     3570
  370 CONTINUE                                                           3571
  380 CONTINUE                                                           3572
C     ********************************************************************3573
C     ************************  SHADING  *********************************3574
C     ********************************************************************3575
      IF (MOVIE.EQ.3) GO TO 390                                          3576
      IF (LI3.EQ.1.AND.LSYM.EQ.0) GO TO 390                              3577
      IF (ISC.NE.-1.OR.NOLIN1(LI,LJ).GT.1) GO TO 390                     3578
      Q=SH(LI,LJ)                                                        3579
      IF (Q.GT.10) Q=10.                                                 3580
      IF (Q.LT.0.) Q=0.                                                  3581
      IQ=Q                                                               3582
      IF (LSYM.EQ.0) CALL SHADE (M1,M2,M3,M4,IQ)                         3583
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      IF (LSYM.EQ.1) CALL SHADE (M1,M2,M3,M4,IQ)                        3584
  390 CONTINUE                                                          3585
C     ******************************************************************3586
C     SHADE LEGEND                                                      3587
C     ******************************************************************3588
      IF (MOVIE.NE.0) GO TO 410                                         3589
      IF (ISC.NE.-1) GO TO 410                                          3590
      IF (LSYM.EQ.1) GO TO 410                                          3591
      DO 400 J=1,10                                                     3592
      CK=J-1                                                            3593
      DELTA=(E2-E1)/10.                                                 3594
      CN1=E1+(J-1)*DELTA                                                3595
      CN2=CN1+DELTA                                                     3596
      DD=2.*DR(1)                                                       3597
      YB=XGRAPH(IHIGH)-DD*(J-1)                                         3598
      CALL NXVDSB (4,YB,T,M2)                                           3599
      YB=M2/102.3                                                       3600
      XA=ZGRAPH(1)-20.*DZ(1)                                            3601
      CALL NXVDSB (3,XA,T,M1)                                           3602
      XA=M1/102.3                                                       3603
      XB=XA+0.25                                                        3604
      XC=XA+1.0                                                         3605
      CALL NUMBER (XA,YB,0.1,CK,0.,-1)                                  3606
      IF (LI1.EQ.14) CALL NUMBER (XB,YB,0.1,CN1,0.,+4)                  3607
      IF (LI1.EQ.14) CALL NUMBER (XC,YB,0.1,CN2,0.,+4)                  3608
      IF (LI1.NE.14) CALL NUMBER (XB,YB,0.1,CN1,0.,+1)                  3609
      IF (LI1.NE.14) CALL NUMBER (XC,YB,0.1,CN2,0.,+1)                  3610
      XDD=ZGRAPH(1)-25.*DZ(1)                                           3611
      YD=XGRAPH(IHIGH)-DD*(J-1)-DD/4.                                   3612
      QZ=(J-1)*7                                                        3613
      XD1=XDD+DD                                                        3614
      YD1=YD+DD                                                         3615
      CALL NXVDSB (3,XD,T,M1)                                           3616
      CALL NXVDSB (3,XD1,T,M3)                                          3617
      CALL NXVDSB (4,YD,T,M2)                                           3618
      CALL NXVDSB (4,YD1,T,M4)                                          3619
      XX1=M1/102.3                                                      3620
      XX2=M3/102.3                                                      3621
      YY1=M2/102.3                                                      3622
      YY2=M4/102.3                                                      3623
      CALL PLOT (XX1,YY1,+3)                                            3624
      CALL PLOT (XX2,YY1,+2)                                            3625
      CALL PLOT (XX2,YY2,+2)                                            3626
      CALL PLOT (XX1,YY2,+2)                                            3627
      CALL PLOT (XX1,YY1,+2)                                            3628
      CALL SHADE (M1,M2,M3,M4,J)                                        3629
  400 CONTINUE                                                          3630
  410 CONTINUE                                                          3631
      IF (LI3.EQ.1.AND.LSYM.EQ.0) GO TO 420                             3632
      IF (IPART.NE.0) CALL PARTCL                                       3633
  420 IF (ISYM.EQ.0) GO TO 430                                          3634
      IF (LSYM.EQ.0) GO TO 220                                          3635
  430 IF (IDET.EQ.2) CALL LABPLT                                        3636
      IF (ISC.NE.-1.OR.IDET.NE.3) GO TO 460                             3637
C     ******************************************************************3638
C     PUNCHED OUTPUT OF SH                                              3639
C     ******************************************************************3640
      PUNCH 480, IHIGH,JHIGH,NCYCLE,DZ(1),DR(1),ZGRAPH(1),XGRAPH(1),(TIT3641
     1LE(I),I=1,8)                                                      3642
      WRITE (6,490) IHIGH,JHIGH,NCYCLE,DZ(1),DR(1),ZGRAPH(1),XGRAPH(1),(3643
     1TITLE(I),I=1,8)                                                   3644
      JCODE=3*(LI1-3)+1                                                 3645
      PUNCH 500, E1,E2,TLABEL(JCODE),TLABEL(JCODE+1),TLABEL(JCODE+2)    3646
      WRITE (6,510) E1,E2,TLABEL(JCODE),TLABEL(JCODE+1),TLABEL(JCODE+2) 3647
```

```
      DO 450 I=ILOW,IHIGH                                                3648
      DO 440 LJ=JLOW,JHIGH                                               3649
      LI=IHIGH+ILOW-I                                                    3650
      IZZ(LJ)=SH(LI,LJ)                                                  3651
      IF (IZZ(LJ).GT.9) IZZ(LJ)=9                                        3652
      IF (IZZ(LJ).LT.0) IZZ(LJ)=0                                        3653
  440 CONTINUE                                                           3654
      PUNCH 520, (IZZ(J),J=1,JHIGH)                                      3655
      WRITE (6,530) (IZZ(J),J=1,JHIGH)                                   3656
  450 CONTINUE                                                           3657
  460 CONTINUE                                                           3658
      IF (IDET.EQ.5) CALL THREED                                         3659
      RETURN                                                             3660
C                                                                        3661
C                                                                        3662
C                                                                        3663
  470 FORMAT (10X,100I1)                                                 3664
  480 FORMAT (I3,I3,I4,4E10.4,7A4,A2)                                    3665
  490 FORMAT (10X,I3,2X,I3,2X,I4,4(1X,E12.4),7A4,A2)                     3666
  500 FORMAT (2E10.4,3A4)                                                3667
  510 FORMAT (10X,2E10.4,5X,3A4)                                         3668
  520 FORMAT (80I1)                                                      3669
  530 FORMAT (5X,80I1)                                                   3670
  540 FORMAT (10X,11HTIME(MSEC) ,E12.4)                                  3671
  550 FORMAT (8X,16H  NCYCLE,T,DT   ,I4,2(1X,E12.4))                     3672
      END                                                                3673
      SUBROUTINE LABPLT (ILIP,ICODE,IPLOT,JPLOT,MDIM)                    3674
C                                                                        3675
C                                                                        3676
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  3677
C     PLOTS TIME AND SPACE HISTORIES                                     3678
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  3679
C                                                                        3680
C                                                                        3681
      DIMENSION TLABEL(102), TLOB(102), IC(34), TLAB(3,3), SYMB(36)      3682
      COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTDL,TZERO,T                  3683
      COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH      3684
      COMMON/P1/XGRAPH(45),ZGRAPH(225),XVELT(45,225),ZVELT(45,225),      3685
     1SH(45,225),DR(45),DZ(225), NOLIN1(45,225),NOLIN2(45,225),ILOW,     3686
     1IHIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),IDIM(10),NCYCLE,ISC,  3687
     2DMN(525),X  (225),Y  (225),IPLOW,IPHIGH,JPLOW,JPHIGH,XPT(50,11),   3688
     3YPT(50,11)                                                         3689
      COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR  3690
     1MIN(10),JRMAX(10),MPODE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG   3691
      COMMON /P3/ ZZ,LI1,LI2,LI3,LI4,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL  3692
     1O,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M  3693
     2OVIE,IDET,IVEL,RPV,ILINE,MZODE(20),ION(3),ISPAT,IZMIN(20),IZMAX(20  3694
     3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM                  3695
C                                                                        3696
      DATA SYMB/1HI,1HJ,1HR,1HZ,1H ,1H ,1HU,1HV,1HP,1HE,1HI,1HC,1HM,1HR,  3697
     11HM,1HB,1HT,1HT,1HT,1HT,1HT,1H ,1HV,1HP,1HS,1HJ,1HJ,1HG,1HN,1HT,1H  3698
     2I,1H ,1H ,1H ,1H ,1H /                                             3699
      DATA TVS/4H VS /                                                   3700
C                                                                        3701
      DATA TLABEL/4H  R-,4HRADI,4HAL  ,4H  Z-,4HAXIA,4HL   ,4H  DE,4HLTA  3702
     1-,4HR   ,4H  DE,4HLTA-,4HZ   ,4H VEL,4HOCIT,4HY-Z ,4H VEL,4HOCIT,4  3703
     2HY-R ,4H  PR,4HESSU,4HRE  ,4HTOTA,4HL EN,4HERGY,4H INT,4HERNA,4HL   3704
     3EN,4H SPE,4HED S,4HOUND,4H  MA,4HCH N,4HO   ,4H   D,4HENSI,4HTY  ,  3705
     44H   ,4HMASS,4H    ,4H  MA,4HGN I,4HND O,4H    ,4H TRR,4H    ,4H    3706
     5  ,4H TZZ,4H    ,4H    ,4H TOO,4H    ,4H    ,4H TRZ,4H    ,4H      3707
     6,4HTIME,4H    ,4H    ,4H DT ,4H    ,4H  VI,4HSCOS,4HITY ,4HMAGN,4H   3708
     7 FLD,4H R  ,4HMAGN,4H FLD,4H Z  ,4H CUR,4HRENT,4H-R  ,4H CUR,4HREN   3709
     8T,4H-Z  ,4H   C,4HP/CV,4H    ,4H CON,4HD EL,4HECTR,4H    ,4H    ,4   3710
     9H    ,4HTEMP,4HERAT,4HURE ,4HSP H,4HEAT ,4HVOL ,4H POT,4HENTI,4HAL   3711
```

```
     $  ,4HHALL,4H PAR,4HMTER,4H CON,4HD TH,4HERML,4H VOR,4HTICI,4HTY  /
C
      DATA TLOB/4H     ,4H CM ,4H     ,4H     ,4H CM ,4H     ,4H     ,4H CM ,
     14H     ,4H     ,4H CM ,4H     ,4H  CM,4H/SEC,4H     ,4H  CM,4H/SEC,4H
     2   ,4H     ,4HATMS,4H     ,4H   E,4HRG/G,4HM    ,4H   E,4HRG/G,4HM
     3,4H  CM,4H/SEC,4H     ,4H     ,4H -- ,4H     ,4H   G,4HM/CM,4H3   ,4H
     4     ,4H GM ,4H     ,4H   G,4HAUSS,4H     ,4H  DY,4HNE/C,4HM2  ,4H  D
     5Y,4HNE/C,4HM2  ,4H  DY,4HNE/C,4HM2  ,4H  DY,4HNE/C,4HM2  ,4H     ,4
     6H SEC,4H     ,4H     ,4H SEC,4H     ,4H GM-,4HCM/S,4HEC  ,4H   G,4HAU
     7SS,4H     ,4H   G,4HAUSS,4H     ,4HABCD,4HL/CM,4H/SEC,4HABCD,4HL/CM,
     84H/SEC,4H     ,4H----,4H     ,4H     ,4H----,4H     ,4H     ,4H     ,4H
     9   ,4H     ,4HDEG ,4HK    ,4H     ,4H----,4H     ,4H     ,4HVOLT,4HS
     $,4H     ,4H----,4H     ,4H     ,4H----,4H     ,4H     ,4H----,4H     /
C
      DATA IC/0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
     10,0,0,0,0/
C
C
C     **********************************************************************
C     PLOT TIME HISTORIES AND SPATIAL DISTRIBUTIONS
C     **********************************************************************
      WRITE (6,160) (TITLE(I),I=1,15)
C     **********************************************************************
C     DEFINING VARIABLES AND CELLS TO BE PLOTTED
C     **********************************************************************
      CL1=KL1
      CL2=KL2
      CL3=KL3
      CL4=KL4
      CIPLOT=IPLOT
      CJPLOT=JPLOT
      ICEX=0
      CALL CHSIZV (1,1)
      DC=50.
      JCODE=3*(ICODE-3)+1
      TLAB(1,1)=TLABEL(JCODE)
      TLAB(1,2)=TLABEL(JCODE+1)
      TLAB(1,3)=TLABEL(JCODE+2)
      TLAB(2,1)=TVS
      JZ=21
      IF (MDIM.EQ.1) JZ=3
      IF (MDIM.EQ.2) JZ=4
      JZ=3*(JZ-3)+1
      TLAB(3,1)=TLABEL(JZ)
      TLAB(3,2)=TLABEL(JZ+1)
      TLAB(3,3)=TLABEL(JZ+2)
      TLAB(2,1)=TLOB(JZ)
      TLAB(2,2)=TLOB(JZ+1)
      TLAB(2,3)=TLOB(JZ+2)
      IE=IC(ICODE)
      IF (ICODE.EQ.0) IE=0
      DO 10 KG=1,ILIP
      Y(KG)=Y(KG)*10.**IE
   10 CONTINUE
      CALL CHSIZV (3,3)
      IF (MDIM.NE.1.AND.MDIM.NE.2) GO TO 30
      IF (MFR.EQ.1) GO TO 30
      DO 20 KG=1,2
      CALL SYMBOL (7.1,.3,.1,19H  I=   ,     J=   , ,0.,19)
      CALL NUMBER (7.54,.3,.1,CL1,0.,-1)
      CALL NUMBER (7.84,.3,.1,CL2,0.,-1)
      CALL NUMBER (8.44,.3,.1,CL3,0.,-1)
      CALL NUMBER (8.84,.3,.1,CL4,0.,-1)
   20 CONTINUE
```

```
      TUB=T*10.**3                                                              3776
      CALL SYMBOL (3.8,9...1,11HTIME (MSEC),0.,11)                              3777
      CALL NUMBER (6.5,9...1,TUB,0.,5)                                          3778
      CALL SYMBOL (4.2,8.65,..1,5HCYCLE,0.,5)                                   3779
      CYCLE=NCYCLE                                                              3780
      CALL NUMBER (5.2,8.65,..1,CYCLE,0.,-1)                                    3781
   30 CONTINUE                                                                  3782
      YB=10.**12                                                                3783
      XL=10.**12                                                                3784
C     ************************************************************************  3785
C     SEARCHING FOR MAXIMUM AND MINIMUM                                         3786
C     ************************************************************************  3787
      YT=-10.**12                                                               3788
      XR=-10.**12                                                               3789
C     ************************************************************************  3790
C     DETERMINING ORDER OF PLOTTING VARIABLES                                   3791
C     ************************************************************************  3792
      DO 40 J=1,ILIP                                                            3793
      IF (X(J).LT.XL) XL=X(J)                                                   3794
      IF (X(J).GT.XR) XR=X(J)                                                   3795
      IF (Y(J).LT.YB) YB=Y(J)                                                   3796
      IF (Y(J).GT.YT) YT=Y(J)                                                   3797
   40 CONTINUE                                                                  3798
C     ************************************************************************  3799
C     SCALING NUMBERS AND RE-WRITING IN EXPONENT FORM                           3800
C     ************************************************************************  3801
      YT=YB+(YT-YB)*1.2                                                         3802
      IF (IHIST.EQ.0) XL=ZLOW                                                   3803
      IF (IHIST.EQ.0) XR=ZHIGH                                                  3804
      YT=YT+1.5*(YT-YB)                                                         3805
      ICEX1=0                                                                   3806
      ICEX2=0                                                                   3807
      W1=0.                                                                     3808
      W2=0.                                                                     3809
      W3=0.                                                                     3810
      W4=0.                                                                     3811
      XXLL=ABS(XL)                                                              3812
      XXRR=ABS(XR)                                                              3813
      YYBB=ABS(YB)                                                              3814
      YYTT=ABS(YT)                                                              3815
      IF (XR.GT.1.) W1=ALOG10(XR)                                               3816
      IF (YT.GT.1.) W3=ALOG10(YT)                                               3817
      IF (XL.LT.-1.) W2=ALOG10(XXLL)                                            3818
      IF (YB.LT.-1.) W4=ALOG10(YYBB)                                            3819
      IF (XR.GT.-1..AND.XR.LT.1..AND.XR.NE.0.) W1=-ALOG10(1./XXRR)              3820
      IF (YT.GT.-1..AND.YT.LT.1..AND.YT.NE.0.) W3=-ALOG10(1./YYTT)              3821
      IF (XL.GT.-1..AND.XL.LT.1..AND.XL.NE.0.) W2=-ALOG10(1./XXLL)              3822
      IF (YB.GT.-1..AND.YB.LT.1..AND.YB.NE.0.) W4=-ALOG10(1./YYBB)              3823
      ICEX1=-W1                                                                 3824
      ICEX2=-W3                                                                 3825
      IF (W1.GT.0..AND.W2.GT.0..AND.W2.GT.W1) ICEX1=-W2                         3826
      IF (W3.GT.0..AND.W4.GT.0..AND.W4.GT.W3) ICEX2=-W4                         3827
      IF (W1.LT.0.AND.W2.LT.0..AND.W1.LT.W2) ICEX1=-W2                          3828
      IF (W3.LT.0.AND.W4.LT.0..AND.W3.LT.W4) ICEX2=-W4                          3829
      YB=YB*10.**ICEX2                                                          3830
      YT=YT*10.**ICEX2                                                          3831
      XL=XL*10.**ICEX1                                                          3832
      XR=XR*10.**ICEX1                                                          3833
      DO 50 KG=1,ILIP                                                           3834
      X(KG)=X(KG)*10.**ICEX1                                                    3835
      Y(KG)=Y(KG)*10.**ICEX2                                                    3836
   50 CONTINUE                                                                  3837
      IE=IE+ICEX                                                                3838
C     ************************************************************************  3839
```

```
C     WARNING ABOUT VARIABLES OF CONSTANT VALUE                                3840
C     ************************************************************************ 3841
      IF (XR.NE.XL.AND.YB.NE.YT) GO TO 60                                      3842
      CALL SYMBOL (3.,6.5,.1,12HNO CHANGE IN,0.,12)                            3843
      CALL SYMBOL (5.2,6.5,.1,TLAB(1,1),0.,4)                                  3844
      CALL SYMBOL (5.60,6.5,.1,TLAB(1,2),0.,4)                                 3845
      CALL SYMBOL (6.00,6.5,.1,TLAB(1,3),0.,4)                                 3846
      IF (JZ.EQ.21) CALL SYMBOL (3.,5.,.1,12HI=      J=    ,0.,12)             3847
      CALL NUMBER (2.5,3.,.1,YB,0.,2)                                          3848
      CALL NUMBER (5.0,3.,.1,YT,0.,2)                                          3849
      CALL SYMBOL (8.,3.,.1,TLOB(JCODE),0.,4)                                  3850
      CALL SYMBOL (8.40,3.,.1,TLOB(JCODE+1),0.,4)                              3851
      CALL SYMBOL (8.80,3.,.1,TLOB(JCODE+2),0.,4)                              3852
      IF (JZ.EQ.21) CALL NUMBER (3.4,4.8,.1,CIPLOT,0.,-1)                      3853
      IF (JZ.EQ.21) CALL NUMBER (4.2,4.8,.1,CJPLOT,0.,-1)                      3854
   60 CONTINUE                                                                 3855
C     ************************************************************************ 3856
C     SETTING UP INTERVALS                                                     3857
C     ************************************************************************ 3858
      IF (XR.EQ.XL.OR.YB.EQ.YT) RETURN                                         3859
      DELT=(XR-XL)/10.                                                         3860
      CALL TRUN (DELT,DELTA)                                                   3861
      IM=XL/DELTA                                                              3862
      CM=IM                                                                    3863
      IF (XL.GT.0.) XL=CM*DELTA                                                3864
      IF (XL.LT.0.) XL=(CM-1.)*DELTA                                           3865
      DX=DELTA                                                                 3866
      DELT=(YT-YB)/10.                                                         3867
      CALL TRUN (DELT,DELTA)                                                   3868
      IF (DELTA.EQ.0.) RETURN                                                  3869
      IM=YB/DELTA                                                              3870
      CM=IM                                                                    3871
      IF (YB.GT.0.) YB=CM*DELTA                                                3872
      IF (YB.LT.0.) YB=(CM-1.)*DELTA                                           3873
      IF (XL.EQ.XR.OR.YB.EQ.YT) RETURN                                         3874
      DY=DELTA                                                                 3875
      CALL NXVOSB (1,XL,XR,-1)                                                 3876
      CALL NXVOSB (2,YB,YT,-1)                                                 3877
      CALL CHSIZV (3,3)                                                        3878
      CALL DXDYV (1,XL,XR,DX,N,I,NX,DC,IERR)                                   3879
      CALL DXDYV (2,YB,YT,DY,M,J,NY,DC,IERR)                                   3880
      LX=2                                                                     3881
      LY=2                                                                     3882
C     ************************************************************************ 3883
C     SETTING GRIDS                                                            3884
C     ************************************************************************ 3885
      CALL SETGRD (XL,XR,YB,YT,DX,DY,LX,LY)                                    3886
      DO 80 J=2,ILIP                                                           3887
      M1=0                                                                     3888
      M2=0                                                                     3889
      M3=0                                                                     3890
      M4=0                                                                     3891
      CALL NXVOSB (3,X(J-1),A3,M1)                                             3892
      CALL NXVOSB (4,Y(J-1),A3,M2)                                             3893
      CALL NXVOSB (3,X(J),A3,M3)                                               3894
      CALL NXVOSB (4,Y(J),A3,M4)                                               3895
      IF (M1.EQ.M3) Y(J)=Y(J-1)                                                3896
      DO 70 LV=1,2                                                             3897
      X3=M3/102.3                                                              3898
      X4=M4/102.3                                                              3899
      IF (MFR.EQ.1.AND.MOD(J,5).EQ.0) CALL SYMBOL (X3,X4,.1,SYMB(ICODE),       3900
     10.,1)                                                                    3901
      CALL LINEV (M1,M2,M3,M4)                                                 3902
   70 CONTINUE                                                                 3903
```

```
   80 CONTINUE                                                          3904
      IF (ICODE.EQ.0) RETURN                                            3905
      DO 130 KX=1,2                                                     3906
      WRITE (6,160) (TITLE(I),I=1,15)                                   3907
      DO 85 KW=1,15                                                     3908
      XCD=2.+KW*0.70                                                    3909
   85 CALL SYMBOL(XCD,9.5,.2,TITLE(KW),0.,4)                            3910
C     ********************************************************************3911
C     PRINTING VARIABLE NAMES AND DIMENSIONS                            3912
C     ********************************************************************3913
      DO 120 MK=1,2                                                     3914
      DO 110 K=1,3                                                      3915
      JK=JCODE-1+K                                                      3916
      C1=K-1                                                            3917
      CX=C1*.40+3.5                                                     3918
      CY1=C1*.40+4.2                                                    3919
      CY2=C1*.40+5.2                                                    3920
      CZ=C1*.40+5.5                                                     3921
      IF (MK.EQ.2) CZ=0.22                                              3922
      IF (MFR.EQ.0) GO TO 100                                           3923
      ICZ=22+(IKT-1)*12                                                 3924
      CZ=ICZ                                                            3925
      CZ=CZ/100.                                                        3926
  100 IF (MK.EQ.1) CALL SYMBOL (CX,.3,.1,TLAB(3,K),0.,4)                3927
      IF (MK.EQ.1) CALL SYMBOL (CZ,.3,.1,TLAB(2,K),0.,4)                3928
      IF (MK.EQ.2) CALL SYMBOL (CZ,CY1,.1,TLABEL(JK),90.,4)             3929
      IF (MK.EQ.2) CALL SYMBOL (CZ,CY2,.1,TLOB(JK),90.,4)               3930
  110 CONTINUE                                                          3931
C     ********************************************************************3932
C     PRINTING ORDER OF VARIABLES (1ST,2ND,3RD,ETC..) TO BE PLOTTED     3933
C     ********************************************************************3934
      IX=32+(IKT-1)*12                                                  3935
      IF (MFR.EQ.0) IX=50                                               3936
      CIX=IX                                                            3937
      CIX=CIX/100.                                                      3938
      IF(MK.EQ.2) CALL SYMBOL(CIX,5.5,.1,1HE,90.,1)                     3939
      IF (MK.EQ.1) CALL SYMBOL (5.00,.2,.1,1HE,0.,1)                    3940
      COUMB=10.**(ICEX2)                                                3941
      IF (MK.EQ.1) CALL NUMBER (5.25,.2,.1,COUMB,0.,-1)                 3942
      COUMB=10.**(ICEX1)                                                3943
      IF (MK.EQ.2) CALL NUMBER (CIX,5.25,.1,COUMB,90.,-1)               3944
  120 CONTINUE                                                          3945
      CALL CHSIZV (3,3)                                                 3946
C     ********************************************************************3947
C     CELL IDENTIFICATION                                               3948
C     ********************************************************************3949
      IF (MDIM.EQ.1.OR.MDIM.EQ.2) GO TO 130                             3950
      CALL SYMBOL (4.,9...1,21H  I=       J=         ,0.,21)            3951
      CALL NUMBER (4.48,9...1,CIPLOT,0.,-1)                             3952
      CALL NUMBER (5.40,9...1,CJPLOT,0.,-1)                             3953
  130 CONTINUE                                                          3954
      IF (MFR.EQ.0) GO TO 150                                           3955
      YK=800-IKT*20                                                     3956
      IK=YK                                                             3957
      CY=YK/102.3                                                       3958
      DO 140 K=1,3                                                      3959
      JK=ICODE                                                          3960
      JK=3*(JK-3)+K                                                     3961
      CX1=K-1                                                           3962
      CX2=CX1*.40+8.                                                    3963
      CALL SYMBOL (CX2,CY,.1,TLOB(JK),0.,4)                             3964
      CALL SYMBOL (9.4,CY,.1,SYMB(ICODE),0.,1)                          3965
  140 CONTINUE                                                          3966
  150 CONTINUE                                                          3967
```

```
      RETURN                                                                    3968
C                                                                               3969
C                                                                               3970
  160 FORMAT (2X,15A4)                                                          3971
      END                                                                       3972
      SUBROUTINE SETGRD (XL,HORZ,YB,VERT,DX,DY,LX,LY)                           3973
C                                                                               3974
C                                                                               3975
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  3976
C     SETTING GRID FOR TIME AND SPACE HISTORIES                                 3977
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  3978
C                                                                               3979
C                                                                               3980
      COMMON /P1/ XGRAPH(25),ZGRAPH(75),XVELT(25,75),ZVELT(25,75),SH(25,        3981
     175),DR(25),DZ(75),NOLIN1(25,75),NOLIN2(25,75),ILOW,IHIGH,JLOW,JHIG       3982
     2H,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC,DMN(525),XLF(75        3983
     3),YLF(75),IPLOW,IPHIGH,JPLOW,JPHIGH,XPT(50,11),YPT(50,11)                 3984
      COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR        3985
     1MIN(10),JRMAX(10),MPODE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG          3986
      COMMON /P3/ ZZ,LI1,LI2,LI3,LI4,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL        3987
     10,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M        3988
     2OVIE,IDET,IVEL,RPV,ILINE,MZODE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20        3989
     3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM                         3990
C                                                                               3991
C                                                                               3992
      DIMENSION XLAB(50), YLAB(50), IRASX(50), IRASY(50)                        3993
C                                                                               3994
C                                                                               3995
      CALL LINEV (1000,100,100,100)                                             3996
      CALL LINEV (100,100,100,1000)                                             3997
      NTX=(HORZ-XL)/DX+1.                                                       3998
      NTY=(VERT-YB)/DY+1.                                                       3999
      XLAB(1)=XL                                                                4000
C     ************************************************************************  4001
C     DEFINING LABELS                                                           4002
C     ************************************************************************  4003
      DO 10 I=2,NTX                                                             4004
   10 XLAB(I)=XLAB(I-1)+DX                                                      4005
      YLAB(1)=YB                                                                4006
      DO 20 I=2,NTY                                                             4007
   20 YLAB(I)=YLAB(I-1)+DY                                                      4008
      DO 30 I=1,NTX                                                             4009
      CALL NXVOSB (3,XLAB(I),T,M1)                                              4010
   30 IRASX(I)=M1                                                               4011
      DO 40 I=1,NTY                                                             4012
      CALL NXVOSB (4,YLAB(I),T,M2)                                              4013
   40 IRASY(I)=M2                                                               4014
      IF (MFR.NE.0) GO TO 60                                                    4015
      DO 45 I=1,NTX,LX                                                          4016
      CALL LINEV (IRASX(I),100,IRASX(I),150)                                    4017
   45 CONTINUE                                                                  4018
      DO 50 I=1,NTY,LY                                                          4019
      CALL LINEV (100,IRASY(I),150,IRASY(I))                                    4020
   50 CONTINUE                                                                  4021
C     ************************************************************************  4022
C     LABELLING ABSCISSA                                                        4023
C     ************************************************************************  4024
   60 CONTINUE                                                                  4025
      LOX=LX                                                                    4026
      IF (NTX.GT.12) LOX=2                                                      4027
      DO 70 I=1,NTX,LOX                                                         4028
      IRASX(I)=IRASX(I)-24                                                      4029
      X1=IRASX(I)/102.3                                                         4030
      Y1=70./102.3                                                              4031
```

```
      CNB=0.12                                                          4032
      NUMB=5                                                            4033
      IF (IHIST.GT.0.OR.ISPAT.GT.0) NUMB=2                              4034
      IF (IHIST.GT.0.OR.ISPAT.GT.0) CNB=0.08                            4035
   70 CALL NUMBER (X1,Y1,CNB,XLAB(I),0.,NUMB)                           4036
C     ****************************************************************  4037
C     LABELLING ORDINATE                                                4038
C     ****************************************************************  4039
      DO 100 I=1,NTY,LY                                                 4040
      ISIG=0                                                            4041
      IF (IRASY(I).GT.430.AND.IRASY(I).LT.640) ISIG=1                   4042
      DO 100 KIJ=1,2                                                    4043
      X1=10./102.3                                                      4044
      Y1=IRASY(I)/102.3                                                 4045
      IF (MFR.NE.0) GO TO 80                                            4046
      IF(ISIG.EQ.0) CALL NUMBER (X1,Y1,.12,YLAB(I),0.,4)                4047
      IF (MFR.EQ.0) GO TO 90                                            4048
   80 ICX=10                                                            4049
      ICY=IRASY(I)                                                      4050
      ICX=ICX+12*IKT                                                    4051
      X1=ICX/102.3                                                      4052
      IF(ISIG.EQ.0) CALL NUMBER (X1,Y1,.12,YLAB(I),90.,2)               4053
   90 CONTINUE                                                          4054
  100 CONTINUE                                                          4055
      RETURN                                                            4056
C                                                                       4057
C                                                                       4058
      END                                                               4059
      SUBROUTINE NXVOSB (INXV,X1,X2,I1)                                 4060
C                                                                       4061
C                                                                       4062
C     ****************************************************************  4063
C     SETTING SCALES                                                    4064
C     ****************************************************************  4065
C                                                                       4066
C                                                                       4067
      GO TO (10,20,30,40), INXV                                         4068
   10 XMIN=X1                                                           4069
      XMAX=X2                                                           4070
      GO TO 50                                                          4071
   20 YMIN=X1                                                           4072
      YMAX=X2                                                           4073
      GO TO 50                                                          4074
   30 I3=900-150                                                        4075
      A3=I3                                                             4076
      A4=150.                                                           4077
      A1=(X1-XMIN)*A3/(XMAX-XMIN)+A4                                    4078
      I1=A1                                                             4079
      GO TO 50                                                          4080
   40 I3=900-150                                                        4081
      A3=I3                                                             4082
      A4=150                                                            4083
      A1=(X1-YMIN)*A3/(YMAX-YMIN)+A4                                    4084
      I1=A1                                                             4085
   50 RETURN                                                            4086
      END                                                               4087
      SUBROUTINE TRUN (XIN,YOUT)                                        4088
C                                                                       4089
C                                                                       4090
C     XXXX
```

```
      YOUT=0.                                                          4096
      IF (XIN.EQ.0.) RETURN                                            4097
      J=1                                                              4098
      Y=ABS(XIN)                                                       4099
      IF (Y.GT.1.) J=-1                                                4100
      I=0                                                              4101
   10 I=I+1                                                            4102
      IF (I.GT.50) RETURN                                              4103
      JI=I*J                                                           4104
      Y1=Y*10.**JI                                                     4105
      IF (J.EQ.-1.AND.Y1.GT.1.) GO TO 10                               4106
      IF (J.EQ.1.AND.Y1.LT.1.) GO TO 10                                4107
      IF (J.GT.0) ITRUNC=Y1                                            4108
      IF (J.LT.0) ITRUNC=Y1*10.                                        4109
      Y1=ITRUNC                                                        4110
      IF (J.GT.0) IE=-JI                                               4111
      IF (J.LT.0) IE=-JI+J                                             4112
      YOUT=Y1*10.**IE*ABS(XIN)/XIN                                     4113
      RETURN                                                           4114
      END                                                              4115
      SUBROUTINE ARROW (IZC,IXC,M1,M2,XCOMP,ZCOMP)                     4116
C                                                                      4117
C                                                                      4118
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4119
C     DRAWS ARROW FOR VECTOR PLOT                                      4120
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4121
C                                                                      4122
C                                                                      4123
      IF (ZCOMP.EQ.0.) ZCOMP=10.**(-6)                                 4124
      VR=ABS(XCOMP/ZCOMP)                                              4125
      VR=ATAN(VR)                                                      4126
      IF (ZCOMP.GT.0.) THETA=SIGN(1.,XCOMP)*VR                         4127
      IF (ZCOMP.LT.0.) THETA=3.1416-SIGN(1.,XCOMP)*VR                  4128
      THETA1=THETA+150./360.*6.28                                      4129
      THETA2=THETA+210./360.*6.28                                      4130
      XCOORD=M1                                                        4131
      YCOORD=M2                                                        4132
      X=IZC                                                            4133
      Y=IXC                                                            4134
      RCOMP=SQRT(ZCOMP**2+XCOMP**2)                                    4135
      RCOMP=RCOMP/2.                                                   4136
      X1=X+COS(THETA1)*RCOMP/4.                                        4137
      X2=X+COS(THETA2)*RCOMP/4.                                        4138
      Y1=Y+SIN(THETA1)*RCOMP/4.                                        4139
      Y2=Y+SIN(THETA2)*RCOMP/4.                                        4140
      IX1=X1                                                           4141
      IX2=X2                                                           4142
      IY1=Y1                                                           4143
      IY2=Y2                                                           4144
      CALL LINEV (IZC,IXC,IX1,IY1)                                     4145
      CALL LINEV (IZC,IXC,IX2,IY2)                                     4146
      CALL LINEV (IX1,IY1,IX2,IY2)                                     4147
      RETURN                                                           4148
      END                                                              4149
      SUBROUTINE PARTCL                                                4150
C                                                                      4151
C                                                                      4152
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4153
C     DRAWS PARTICLES                                                  4154
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4155
C                                                                      4156
C                                                                      4157
      COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTDL,TZERO,T                4158
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                         4159
```

```
      COMMON/P1/R     (45),Z     (225),V     (45,225),U     (45,225),
     1SH(45,225),FR(45),FZ(225),  NOLIN1(45,225),NOLIN2(45,225),ILOW,
     1IHIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC,
     2DMN(525),XLF(225),YLF(225),IPLOW,IPHIGH,JPLOW,JPHIGH,XPT(50,11),
     3YPT(50,11)
      COMMON /P3/ ZZ,LI1,LI2,LI3,LI4,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL
     1O,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M
     2OVIE,IDET,IVEL,RPV,ILINE,MZODE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20
     3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM
      DATA CKT/0./
C
C
      X1=Z(1)
C     ***************************************************************
C     DETERMINING SIZE OF POINT TO BE PLOTTED
C     ***************************************************************
      X2=Z(2)
      CALL NXVOSB (3,X1,S,NX1)
      CALL NXVOSB (3,X2,S,NX2)
      NDIF=IABS(NX2-NX1)
      CPT=NDIF
      CPT=CPT*1.0/102.3
      IF (CPT.GT.1..OR.CPT.LT..01) CPT=0.25
      DKT=1.
      IF (ISYM.GT.0.AND.CKT.GT.0.) DKT=0.5
      CKT=CKT+DKT
      IKT=CKT
      IF (IKT.EQ.1) TLOW=TPLTMI
      DT=T-TLOW
      TLOW=T
C     ***************************************************************
C     DEFINING THE LOCATION OF A NEW SET OF TRACER PARTICLES
C     ***************************************************************
      IF (DT.LE.0.) RETURN
      IF (IKT.GT.NPTS) GO TO 20
      K=0
      DO 10 M=IPLOW,IPHIGH
      DO 10 L=JPLOW,JPHIGH
      IF (IPLOW.NE.IPHIGH) K=M
      IF (JPLOW.NE.JPHIGH) K=L
      XPT(K,IKT)=Z(L)
      YPT(K,IKT)=R(M)
   10 CONTINUE
      KK=K
   20 CONTINUE
C     ***************************************************************
C     REDEFINING LOCATION OF TRACER PARTICLES
C     ***************************************************************
      IF (IKT.GT.NPTS) IKT=NPTS
      IF (IKT.GE.10) IKT=10
      DO 30 M=2,IKT
      DO 30 L1=IPLOW,IPHIGH
      DO 30 L2=JPLOW,JPHIGH
      IF (IPLOW.NE.IPHIGH) K=L1
      IF (JPLOW.NE.JPHIGH) K=L2
      X=XPT(K,M)
      Y=YPT(K,M)
      XL=X
      YL=Y
      IF (ISYM.EQ.1) XL=ABS(XL)
      IF (ISYM.EQ.2) YL=ABS(YL)
      CALL CELL (XL,YL,II,JJ)
      JP=JJ+1
      IF (X.LE.Z(JJ).AND.JJ.GT.1) JP=JJ-1
```

```
      IP=II+1                                                                  4224
      RR=R(II)                                                                 4225
      IF (Y.LE.RR.AND.II.GT.1) IP=II-1                                         4226
      DZ=Z(JJ+1)-Z(JJ)                                                         4227
      DR=R(II+1)-R(II)                                                         4228
      VEL1X=U(II,JJ)+(X-Z(JJ))/DZ*(U(IP,JJ)-U(II,JJ))                          4229
      VEL2X=U(II,JP)+(X-Z(JJ))/DZ*(U(IP,JP)-U(II,JP))                          4230
      VEL1Y=V(II,JJ)+(Y-RR)/DR*(V(IP,JJ)-V(II,JJ))                             4231
      VEL2Y=V(IP,JJ)+(Y-RR)/DR*(V(IP,JP)-V(IP,JJ))                             4232
      XPT(K,M)=XPT(K,M)+(VEL1X+(X-Z(JJ))/DZ*(VEL2X-VEL1X))*DT                  4233
      YPT(K,M)=YPT(K,M)+(VEL1Y+(Y-RR)/DR*(VEL2Y-VEL1Y))*DT                     4234
   30 CONTINUE                                                                 4235
C     ************************************************************************ 4236
C     PLOTTING TRACER PARTICLES                                                4237
C     ************************************************************************ 4238
      MLOW=JPLOW                                                               4239
      IF (IPLOW.NE.IPHIGH) MLOW=IPLOW                                          4240
      DO 40 M=MLOW,KK                                                          4241
      DO 40 J=2,IKT                                                            4242
      X=XPT(M,J)                                                               4243
      Y=YPT(M,J)                                                               4244
      CALL NXVOSB (3,X,S,N1)                                                   4245
      CALL NXVOSB (4,Y,S,N2)                                                   4246
      IF (X.GT.Z(JP2).OR.X.LT.Z(1).OR.Y.GT.R(KP2).OR.Y.LT.R(1)) GO TO 40       4247
      CALL PLOTV (N1,N2,44)                                                    4248
   40 CONTINUE                                                                 4249
      RETURN                                                                   4250
C                                                                              4251
      END                                                                      4252
      SUBROUTINE CELL (X,Y,II,JJ)                                              4253
C                                                                              4254
C                                                                              4255
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4256
C     SELECTS CELL CONTAINING PARTICLES                                        4257
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4258
C                                                                              4259
C                                                                              4260
      COMMON/P1/R      (45),Z      (225),XVELT(45,225),ZVELT(45,225),          4261
     1SH(45,225),DR(45),DZ(225),  NOLIN1(45,225),NOLIN2(45,225),ILOW,         4262
     1IHIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC,       4263
     2DMN(525),XLF(225),YLF(225),IPLOW,IPHIGH,JPLOW,JPHIGH,XPT(50,11),         4264
     3YPT(50,11)                                                               4265
      COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR       4266
     1MIN(10),JRMAX(10),MPODE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG         4267
      COMMON /P3/ ZZ,LI1,LI2,LI3,LI4,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL       4268
     1O,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M       4269
     2OVIE,IDET,IVEL,RPV,ILINE,MZODE(20),ION(3),ISPAT,IZMIN(20),IZMAX(20       4270
     3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM                        4271
      COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                                 4272
C                                                                              4273
C                                                                              4274
      JLO=1                                                                    4275
      JHIG=JP2                                                                 4276
      JMID1=0                                                                  4277
   10 JMID=(JLO+JHIG)/2                                                        4278
      IF (JMID1.EQ.JMID) GO TO 20                                              4279
      JMID1=JMID                                                               4280
      ZX=Z(JMID)                                                               4281
      IF (ISYM.EQ.1) ZX=ABS(ZX)                                                4282
      IF (ZX.GE.X) JHIG=JMID                                                   4283
      IF (ZX.LE.X) JLO=JMID                                                    4284
      JJ=JMID                                                                  4285
      GO TO 10                                                                 4286
   20 IMID1=0                                                                  4287
```

```
      ILO=1                                                              4288
      IHIG=KP2                                                           4289
   30 IMID=(ILO+IHIG)/2                                                  4290
      IF (IMID1.EQ.IMID) GO TO 40                                        4291
      IMID1=IMID                                                         4292
      RR=R(IMID)                                                         4293
      IF (ISYM.EQ.2) RR=ABS(RR)                                          4294
      IF (RR.GE.Y) IHIG=IMID                                             4295
      IF (RR.LE.Y) ILO=IMID                                              4296
      II=IMID                                                            4297
      GO TO 30                                                           4298
   40 CONTINUE                                                           4299
      RETURN                                                             4300
      END                                                                4301
      SUBROUTINE SHADE (M1,M2,M3,M4,IQ)                                  4302
C                                                                        4303
C                                                                        4304
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4305
C     SHADE OR GREY LEVEL SCALING                                        4306
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4307
C                                                                        4308
C                                                                        4309
      DIMENSION IPAT0(16),IPAT1(16),IPAT2(16),IPAT3(16),IPAT4(16),       4310
     1IPAT5(16),IPAT6(16),IPAT7(16),IPAT8(16),IPAT9(16)                  4311
      DIMENSION XARRAY(4),YARRAY(4)                                      4312
      DATA IPAT0/16*Z0000/                                               4313
      DATA IPAT1/7*Z0000,Z0100,8*Z0000/                                  4314
      DATA IPAT2/4*Z0000,Z0800,7*Z0000,Z0010,3*Z0000/                    4315
      DATA IPAT3/3*Z0000,Z1010,7*Z0000,Z1010,4*Z0000/                    4316
      DATA IPAT4/2*Z0000,Z2020,3*Z0000,Z0202,3*Z0000,Z2020,3*Z0000,Z0202 4317
     1,Z0000/                                                            4318
      DATA IPAT5/2*Z0000,Z2222,Z0000,2*Z0000,Z2222,Z0000,2*Z0000,Z2222,  4319
     1Z0000,2*Z0000,Z2222,Z0000/                                         4320
      DATA IPAT6/Z8888,Z0000,Z2222,Z0000,Z8888,Z0000,Z2222,Z0000,Z8888,  4321
     1Z0000,Z2222,Z0000,Z8888,Z0000,Z2222,Z0000/                         4322
      DATA IPAT7/ZAAAA,Z0000,Z5555,Z0000,ZAAAA,Z0000,Z5555,Z0000,        4323
     1ZAAAA,Z0000,Z5555,Z0000,ZAAAA,Z0000,Z5555,Z0000/                   4324
      DATA IPAT8/ZAAAA,Z5555,ZAAAA,Z5555,ZAAAA,Z5555,ZAAAA,Z5555,ZAAAA,Z 4325
     15555,ZAAAA,Z5555,ZAAAA,Z5555,ZAAAA,Z5555/                         4326
      DATA IPAT9/16*ZFFFF/                                               4327
      XARRAY(1)=M1/102.3                                                 4328
      XARRAY(2)=M3/102.3                                                 4329
      XARRAY(3)=M3/102.3                                                 4330
      XARRAY(4)=M1/102.3                                                 4331
      YARRAY(1)=M2/102.3                                                 4332
      YARRAY(2)=M2/102.3                                                 4333
      YARRAY(3)=M4/102.3                                                 4334
      YARRAY(4)=M4/102.3                                                 4335
      IQ=IQ-1                                                            4336
      IF(IQ.GT.9) IQ=9                                                   4337
      IF(IQ.EQ. 0) CALL TONE(0.,0.,IPAT0,-16)                            4338
      IF(IQ.EQ. 1) CALL TONE(0.,0.,IPAT1,-16)                            4339
      IF(IQ.EQ. 2) CALL TONE(0.,0.,IPAT2,-16)                            4340
      IF(IQ.EQ. 3) CALL TONE(0.,0.,IPAT3,-16)                            4341
      IF(IQ.EQ. 4) CALL TONE(0.,0.,IPAT4,-16)                            4342
      IF(IQ.EQ. 5) CALL TONE(0.,0.,IPAT5,-16)                            4343
      IF(IQ.EQ. 6) CALL TONE(0.,0.,IPAT6,-16)                            4344
      IF(IQ.EQ. 7) CALL TONE(0.,0.,IPAT7,-16)                            4345
      IF(IQ.EQ. 8) CALL TONE(0.,0.,IPAT8,-16)                            4346
      IF(IQ.EQ. 9) CALL TONE(0.,0.,IPAT9,-16)                            4347
      CALL TONE(XARRAY,YARRAY,4,1)                                       4348
      RETURN                                                             4349
      END                                                                4350
      SUBROUTINE LEVEL (T,X,Y,II,JJ,S,LL,KK)                             4351
```

```
C                                                                       4352
C                                                                       4353
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4354
C     CONTOUR PLOT DEVELOPED BY ARO, ARNOLD AFS, TENN.                  4355
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4356
C                                                                       4357
C                                                                       4358
      DIMENSION T(II,JJ), X(II,JJ), Y(II,JJ)                            4359
      DIMENSION S(KK), LL(KK)                                           4360
C                                                                       4361
C                                                                       4362
      IMAX=II-1                                                         4363
      JMAX=JJ-1                                                         4364
      DO 480 J=1,JMAX                                                   4365
      KR=0                                                              4366
      IF ((J/2)*2.EQ.J) KR=1                                            4367
      DO 480 III=1,IMAX                                                 4368
      I=III                                                             4369
      IF (KR.EQ.1) I=IMAX+1-III                                         4370
C     ESTABLISH QUADRILATERAL TO BE SEARCHED                            4371
      X1=X(I,J)                                                         4372
      X2=X(I+1,J)                                                       4373
      X3=X(I+1,J+1)                                                     4374
      X4=X(I,J+1)                                                       4375
      Y1=Y(I,J)                                                         4376
      Y2=Y(I+1,J)                                                       4377
      Y3=Y(I+1,J+1)                                                     4378
      Y4=Y(I,J+1)                                                       4379
      T1=T(I,J)                                                         4380
      T2=T(I+1,J)                                                       4381
      T3=T(I+1,J+1)                                                     4382
      T4=T(I,J+1)                                                       4383
      DO 480 M=1,KK                                                     4384
      TISO=S(M)                                                         4385
      L=LL(M)                                                           4386
      S1=TISO-T1                                                        4387
      S2=TISO-T2                                                        4388
      S3=TISO-T3                                                        4389
      S4=TISO-T4                                                        4390
      S12=S1*S2                                                         4391
      S23=S2*S3                                                         4392
      S34=S3*S4                                                         4393
      S41=S4*S1                                                         4394
      K=1                                                               4395
      IF (S1) 20,10,20                                                  4396
   10 K=2                                                               4397
      KL=1                                                              4398
   20 IF (S2) 40,30,40                                                  4399
   30 K=K+1                                                             4400
      KL=2                                                              4401
   40 IF (S3) 60,50,60                                                  4402
   50 K=K+1                                                             4403
      KL=3                                                              4404
   60 IF (S4) 80,70,80                                                  4405
   70 K=K+1                                                             4406
      KL=4                                                              4407
   80 GO TO (300,90,140,270,270), K                                     4408
   90 GO TO (100,110,120,130), KL                                       4409
  100 CALL POINT (S23,S34,S2,S3,T4,T3,T2,X1,Y1,X2,Y2,X3,Y3,X4,Y4,L)     4410
      GO TO 480                                                         4411
  110 CALL POINT (S34,S41,S3,S4,T1,T4,T3,X2,Y2,X3,Y3,X4,Y4,X1,Y1,L)     4412
      GO TO 480                                                         4413
  120 CALL POINT (S41,S12,S4,S1,T2,T1,T4,X3,Y3,X4,Y4,X1,Y1,X2,Y2,L)     4414
      GO TO 480                                                         4415
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  130 CALL POINT (S12,S23,S1,S2,T3,T2,T1,X4,Y4,X1,Y1,X2,Y2,X3,Y3,L)          4416
      GO TO 480                                                              4417
  140 KLL=KL-1                                                               4418
      GO TO (150,170,200), KLL                                               4419
  150 CALL DRAW (L,X1,Y1,X2,Y2)                                              4420
      IF (S34.LT.0.) GO TO 160                                               4421
      GO TO 480                                                              4422
  160 TP=S3/(T4-T3)                                                          4423
      PX1=X3+TP*(X4-X3)                                                      4424
      PY1=Y3+TP*(Y4-Y3)                                                      4425
      PX2=TP*(X1-X2)+X2                                                      4426
      PY2=TP*(Y1-Y2)+Y2                                                      4427
      GO TO 470                                                              4428
  170 IF (S2.EQ.0.) GO TO 180                                                4429
      CALL DRAW (L,X1,Y1,X3,Y3)                                              4430
      GO TO 480                                                              4431
  180 CALL DRAW (L,X3,Y3,X2,Y2)                                              4432
      IF (S41.LT.0.) GO TO 190                                               4433
      GO TO 480                                                              4434
  190 TP=S4/(T1-T4)                                                          4435
      PX1=X4+TP*(X1-X4)                                                      4436
      PY1=Y4+TP*(Y1-Y4)                                                      4437
      PX2=TP*(X2-X3)+X3                                                      4438
      PY2=TP*(Y2-Y3)+Y3                                                      4439
      GO TO 470                                                              4440
  200 IF (S2) 220,210,220                                                    4441
  210 CALL DRAW (L,X2,Y2,X4,Y4)                                              4442
      GO TO 480                                                              4443
  220 IF (S3) 250,230,250                                                    4444
  230 IF (J.EQ.JMAX) CALL DRAW (L,X3,Y3,X4,Y4)                               4445
      IF (S12) 240,480,240                                                   4446
  240 TP=S1/(T2-T1)                                                          4447
      PX1=X1+TP*(X2-X1)                                                      4448
      PY1=Y1+TP*(Y2-Y1)                                                      4449
      PX2=TP*(X3-X4)+X4                                                      4450
      PY2=TP*(Y3-Y4)+Y4                                                      4451
      GO TO 470                                                              4452
  250 IF (I.EQ.1) CALL DRAW (L,X1,Y1,X4,Y4)                                  4453
      IF (S23) 260,480,480                                                   4454
  260 TP=S2/(T3-T2)                                                          4455
      PX1=X2+TP*(X3-X2)                                                      4456
      PY1=Y2+TP*(Y3-Y2)                                                      4457
      PX2=TP*(X4-X1)+X1                                                      4458
      PY2=TP*(Y4-Y1)+Y1                                                      4459
      GO TO 470                                                              4460
  270 IF (S2.NE.0.0) GO TO 280                                               4461
      IF (S1.EQ.0.0) CALL DRAW (L,X2,Y2,X1,Y1)                               4462
      IF (S3.EQ.0.0) CALL DRAW (L,X2,Y2,X3,Y3)                               4463
  280 IF (J.NE.JMAX) GO TO 290                                               4464
      IF (S4.NE.0.0) GO TO 480                                               4465
      IF (S3.EQ.0.0) CALL DRAW (L,X4,Y4,X3,Y3)                               4466
  290 IF (I.NE.1) GO TO 480                                                  4467
      IF (S1.EQ.0.0) CALL DRAW (L,X4,Y4,X1,Y1)                               4468
      GO TO 480                                                              4469
C     SEARCH P1-P2                                                           4470
  300 K=0                                                                    4471
      IF (S12) 310,320,320                                                   4472
  310 TP=S1/(T2-T1)                                                          4473
      K=1                                                                    4474
      PX1=X1+TP*(X2-X1)                                                      4475
      PY1=Y1+TP*(Y2-Y1)                                                      4476
C     SEARCH P2-P3                                                           4477
  320 IF (S23) 330,360,360                                                   4478
  330 TP=S2/(T3-T2)                                                          4479
```

```
      IF (K) 340,350,340                                                4480
C     CHECK FOR QUADRILATERAL WITH 4 INTERSECTIONS                      4481
  340 IF (S34.LT.0.0.AND.S41.LT.0.0) GO TO 430                          4482
      PX2=X2+TP*(X3-X2)                                                 4483
      PY2=Y2+TP*(Y3-Y2)                                                 4484
      GO TO 470                                                         4485
  350 K=K+1                                                             4486
      PX1=X2+TP*(X3-X2)                                                 4487
      PY1=Y2+TP*(Y3-Y2)                                                 4488
C     SEARCH P3-P4                                                      4489
  360 IF (S34) 370,400,400                                              4490
  370 TP=S3/(T4-T3)                                                     4491
      XP=X4-X3                                                          4492
      YP=Y4-Y3                                                          4493
      IF (K) 380,390,380                                                4494
  380 PY2=Y3+TP*YP                                                      4495
      PX2=X3+TP*XP                                                      4496
      GO TO 470                                                         4497
  390 K=K+1                                                             4498
      PY1=Y3+TP*YP                                                      4499
      PX1=X3+TP*XP                                                      4500
C     SEARCH P4-P1                                                      4501
  400 IF (S41) 410,480,480                                              4502
  410 IF (K) 420,480,420                                                4503
  420 TP=S4/(T1-T4)                                                     4504
      PX2=X4+TP*(X1-X4)                                                 4505
      PY2=Y4+TP*(Y1-Y4)                                                 4506
      GO TO 470                                                         4507
  430 TP=S3/(T4-T3)                                                     4508
      PX2=X3+TP*(X4-X3)                                                 4509
      IF ((PX1-X1)/(X2-X1)-(PX2-X4)/(X3-X4)) 440,450,460                4510
  440 TP=S4/(T1-T4)                                                     4511
      PX2=X4+TP*(X1-X4)                                                 4512
      PY2=Y4+TP*(Y1-Y4)                                                 4513
      CALL DRAW (L,PX1,PY1,PX2,PY2)                                     4514
      TP=S2/(T3-T2)                                                     4515
      PX1=X2+TP*(X3-X2)                                                 4516
      PY1=Y2+TP*(Y3-Y2)                                                 4517
      TP=S3/(T4-T3)                                                     4518
      PX2=X3+TP*(X4-X3)                                                 4519
      PY2=Y3+TP*(Y4-Y3)                                                 4520
      GO TO 470                                                         4521
  450 PY2=Y3+TP*(Y4-Y3)                                                 4522
      CALL DRAW (L,PX1,PY1,PX2,PY2)                                     4523
      TP=S2/(T3-T2)                                                     4524
      PX1=X2+TP*(X3-X2)                                                 4525
      PY1=Y2+TP*(Y3-Y2)                                                 4526
      TP=S4/(T1-T4)                                                     4527
      PX2=X4+TP*(X1-X4)                                                 4528
      PY2=Y4+TP*(Y1-Y4)                                                 4529
      GO TO 470                                                         4530
  460 TP=S2/(T3-T2)                                                     4531
      PX2=X2+TP*(X3-X2)                                                 4532
      PY2=Y2+TP*(Y3-Y2)                                                 4533
      CALL DRAW (L,PX1,PY1,PX2,PY2)                                     4534
      TP=S3/(T4-T3)                                                     4535
      PX1=X3+TP*(X4-X3)                                                 4536
      PY1=Y3+TP*(Y4-Y3)                                                 4537
      TP=S4/(T1-T4)                                                     4538
      PX2=X4+TP*(X1-X4)                                                 4539
      PY2=Y4+TP*(Y1-Y4)                                                 4540
  470 CALL DRAW (L,PX1,PY1,PX2,PY2)                                     4541
  480 CONTINUE                                                          4542
      RETURN                                                            4543
```

```
      END                                                                4544
      SUBROUTINE POINT (S23,S34,S2,S3,T4,T3,T2,X1,Y1,X2,Y2,X3,Y3,X4,Y4,L 4545
     1)                                                                  4546
C                                                                        4547
C                                                                        4548
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4549
C     SETTING UP CONTOURS                                                4550
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4551
C                                                                        4552
C                                                                        4553
      KT=1                                                               4554
      IF (S23) 10,20,20                                                  4555
   10 KT=2                                                               4556
      TP=S2/(T3-T2)                                                      4557
      PX1=X2+TP*(X3-X2)                                                  4558
      PY1=Y2+TP*(Y3-Y2)                                                  4559
   20 IF (S34) 30,40,40                                                  4560
   30 TP=S3/(T4-T3)                                                      4561
      KT=KT+2                                                            4562
   40 GO TO (90,60,50,70), KT                                            4563
   50 PX1=X3+TP*(X4-X3)                                                  4564
      PY1=Y3+TP*(Y4-Y3)                                                  4565
   60 PX2=X1                                                             4566
      PY2=Y1                                                             4567
      GO TO 80                                                           4568
   70 PX2=X3+TP*(X4-X3)                                                  4569
      PY2=Y3+TP*(Y4-Y3)                                                  4570
   80 CALL DRAW (L,PX1,PY1,PX2,PY2)                                      4571
   90 RETURN                                                             4572
      END                                                                4573
      SUBROUTINE DRAW (L,PX1,PY1,PX2,PY2)                                4574
C                                                                        4575
C                                                                        4576
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4577
C     DRAWS CONTOUR                                                      4578
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4579
C                                                                        4580
C                                                                        4581
      COMMON /MOVE/ XX(4),YY(4)                                          4582
C                                                                        4583
C                                                                        4584
      I1=PX1*102.3                                                       4585
      I2=PY1*102.3                                                       4586
      I3=PX2*102.3                                                       4587
      I4=PY2*102.3                                                       4588
      CALL LINEV (I1,I2,I3,I4)                                           4589
      RETURN                                                             4590
      END                                                                4591
      SUBROUTINE THREED                                                  4592
C                                                                        4593
C                                                                        4594
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4595
C     SETS UP THREE-DIMENSIONAL PLOTS                                    4596
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4597
C                                                                        4598
C                                                                        4599
      COMMON/P1/XGRAPH(45),ZGRAPH(225),XVELT(45,225),ZVELT(45,225),      4600
     1SH(45,225),DR(45),DZ(225),  NOLIN1(45,225),NOLIN2(45,225),ILOW,    4601
     1IHIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC, 4602
     2DMN(525),XLF(225),YLF(225),IPLOW,IPHIGH,JPLOW,JPHIGH,XPT(50,11),   4603
     3YPT(50,11)                                                         4604
      COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR 4605
     1MIN(10),JRMAX(10),MPODE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG   4606
      COMMON /P3/ ZZ,LI1,LI2,LI3,LI4,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL 4607
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```
      10,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M      4608
      20VIE,IDET,IVEL,RPV,ILINE,MZODE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20      4609
      3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM                       4610
       COMMON /P4/ MASK(2000),VERTEX(16),XG(45),ZG(225),YY(225),XXG(225),      4611
      1ZSH(01,001)                                                             4612
C                                                                              4613
C                                                                              4614
C     ************************************************************************ 4615
C     SETS UP "X,Y,Z" DATA FOR TWO INDIVIDUAL 3-D PLOT PACKAGES                4616
C     ************************************************************************ 4617
      ID3=1                                                                    4618
      IHIGH=IHIGH+1                                                            4619
      JHIGH=JHIGH+1                                                            4620
      NRA=IHIGH                                                                4621
      NCA=JHIGH                                                                4622
      IOPT=0                                                                   4623
      ICROSS=1                                                                 4624
      X1=1                                                                     4625
      X2=NRA+1                                                                 4626
      Y1=1                                                                     4627
      Y2=NCA+1                                                                 4628
      SCL=0.5                                                                  4629
C     ************************************************************************ 4630
C     PACKAGE "ONE"                                                            4631
C     ************************************************************************ 4632
      CALL FRAMEV (3)                                                          4633
      XO=5.                                                                    4634
      YO=12.                                                                   4635
      CN1=45.                                                                  4636
      CN2=225.                                                                 4637
      DO 10 J=1,JHIGH                                                          4638
      IF (J.GT.1) ZGG=ZGRAPH(J-1)+DZ(J-1)/2.                                   4639
      IF (J.EQ.1) ZGG=ZGRAPH(J)-DZ(J)/2.                                       4640
      CALL NXVOSB (3,ZGG,T,M1)                                                 4641
      ZG(J)=(M1-150)/102.3+1.                                                  4642
   10 CONTINUE                                                                 4643
      DO 20 I=1,IHIGH                                                          4644
      IF (I.GT.1) XGG=XGRAPH(I-1)+DR(I-1)/2.                                   4645
      IF (I.EQ.1) XGG=XGRAPH(I)-DR(I)/2.                                       4646
      CALL NXVOSB (4,XGG,T,M1)                                                 4647
      XG(I)=(M1-150)/102.3+1.                                                  4648
   20 CONTINUE                                                                 4649
      KPH=IHIGH                                                                4650
C     ************************************************************************ 4651
C     CROSS-HATCH LINES RUNNING IN ONE DIRECTION                               4652
C     ************************************************************************ 4653
      DO 40 NLINE=1,KPH                                                        4654
      NLIN=NLINE                                                               4655
      XX=XG(NLINE)                                                             4656
      DO 30 NJ=1,JHIGH                                                         4657
      M=NLIN                                                                   4658
      N=NJ                                                                     4659
      MM1=M-1                                                                  4660
      NM1=N-1                                                                  4661
      IF (M.EQ.1) MM1=M                                                        4662
      IF (N.EQ.1) NM1=N                                                        4663
      IF (M.EQ.IHIGH) M=MM1                                                    4664
      IF (N.EQ.JHIGH) N=NM1                                                    4665
      YY(NJ)=1.                                                                4666
      NPP=0                                                                    4667
      IF (NOLIN1(M,N).GT.1.OR.NOLIN1(MM1,N).GT.1.OR.NOLIN1(MM1,NM1).GT.1       4668
     1.OR.NOLIN1(M,NM1).GT.1) NPP=1                                            4669
      IF (NPP.EQ.0) YY(NJ)=(SH(M,N)+SH(MM1,N)+SH(MM1,NM1)+SH(M,NM1))/4.*       4670
     1SCL+1.                                                                   4671
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   30 CONTINUE                                                          4672
      CALL PLOT3D (0011,XX,YY,ZG,0.,1.,1.,NLINE,JHIGH,CN1,CN2,XO,YO,10.,4673
     1MASK,0)                                                           4674
   40 CONTINUE                                                          4675
C     ********************************************************************4676
C     CROSS-HATCH LINES RUNNING IN THE OTHER DIRECTION                  4677
C     ********************************************************************4678
      DO 60 NLINE=1,JHIGH                                               4679
      ZZ=ZG(NLINE)                                                      4680
      DO 50 NI=1,KPH                                                    4681
      NLIN=NI                                                           4682
      M=NI                                                              4683
      N=NLINE                                                           4684
      MM1=M-1                                                           4685
      NM1=N-1                                                           4686
      IF (M.EQ.1) MM1=M                                                 4687
      IF (N.EQ.1) NM1=N                                                 4688
      IF (M.EQ.IHIGH) M=MM1                                             4689
      IF (N.EQ.JHIGH) N=NM1                                             4690
      YY(NI)=1.                                                         4691
      NPP=0                                                             4692
      IF (NOLIN1(M,N).GT.1.OR.NOLIN1(MM1,N).GT.1.OR.NOLIN1(MM1,NM1).GT.1 4693
     1.OR.NOLIN1(M,NM1).GT.1) NPP=1                                     4694
      IF (NPP.EQ.0) YY(NI)=(SH(M,N)+SH(MM1,N)+SH(MM1,NM1)+SH(M,NM1))/4.*4695
     1SCL+1.                                                            4696
C     ZSH(NI,NLINE)=YY(NI)                                              4697
   50 CONTINUE                                                          4698
      CALL PLOT3D (1110,XG,YY,ZZ,1.,1.,0.,NLINE,KPH,CN1,CN2,XO,YO,10.,MA4699
     1SK,VERTEX)                                                        4700
   60 CONTINUE                                                          4701
      CALL FRAMER (3,VERTEX,MASK)                                       4702
      IHIGH=IHIGH-1                                                     4703
      JHIGH=JHIGH-1                                                     4704
C     ********************************************************************4705
C     PACKAGE "TWO"                                                     4706
C     ********************************************************************4707
      IF (ID3.EQ.1) RETURN                                              4708
      IVIEW=1                                                           4709
      CALL PLTMTX (ZSH,NRA,NCA,IVIEW,IOPT,ICROSS,X1,X2,Y1,Y2)           4710
      RETURN                                                            4711
      END                                                               4712
      SUBROUTINE PLOT3D (IVXYZ,XDATA,YDATA,ZDATA,XSCALE,YSCALE,ZSCALE,NL4713
     1INE,NPNTS,PHI,THETA,XREF,YREF,XLENTH,MASK,VERTEX)                  4714
C                                                                       4715
C                                                                       4716
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX4717
C     3-D PLOT ROUTINE DEVELOPED BY THE U OF TEXAS, MATH DEPT.          4718
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX4719
C                                                                       4720
C                                                                       4721
      INTEGER HIGH,OLDHI,OLDLOW                                         4722
      DIMENSION XDATA(1), YDATA(1), ZDATA(1), MASK(1), VERTEX(1)        4723
      DATA INIT,JVXYZ,SPHI,STHETA/-1,-1,-1.0E70,-1.0E70/                4724
C                                                                       4725
C                                                                       4726
      IF (NLINE.EQ.0) GO TO 640                                         4727
      IF (NLINE.NE.1) GO TO 20                                          4728
      PIPI=100.0                                                        4729
      NYPI=1090                                                         4730
      I=NYPI+100                                                        4731
      CALL PLOT (0.0,0.0,-3)                                            4732
      LIMITX=XLENTH*PIPI+0.5                                            4733
      I=LIMITX+LIMITX                                                   4734
      DO 10 K=1,I                                                       4735
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      MASK(K)=INIT                                                    4736
   10 CONTINUE                                                        4737
      INIT=-1                                                         4738
      INCI=-1                                                         4739
      I=0                                                             4740
   20 IF (JVXYZ.EQ.IVXYZ) GO TO 70                                    4741
      JVXYZ=IVXYZ                                                     4742
      INDZ=1                                                          4743
      INDY=1                                                          4744
      INDX=1                                                          4745
      INDV=1                                                          4746
      IF (JVXYZ.LT.1000) GO TO 30                                     4747
      INDV=2                                                          4748
      JVXYZ=JVXYZ-1000                                                4749
   30 IF (JVXYZ.LT.100) GO TO 40                                      4750
      INDX=2                                                          4751
      JVXYZ=JVXYZ-100                                                 4752
   40 IF (JVXYZ.LT.10) GO TO 50                                       4753
      INDY=2                                                          4754
      JVXYZ=JVXYZ-10                                                  4755
   50 IF (JVXYZ.LT.1) GO TO 60                                        4756
      INDZ=2                                                          4757
   60 JVXYZ=IVXYZ                                                     4758
   70 IF (PHI.EQ.SPHI.AND.THETA.EQ.STHETA) GO TO 80                   4759
      SPHI=SIN(.0174533*PHI)                                          4760
      CPHI=COS(.0174533*PHI)                                          4761
      STHETA=SIN(.0174533*THETA)                                      4762
      CTHETA=COS(.0174533*THETA)                                      4763
      A11=CPHI                                                        4764
      A13=-SPHI                                                       4765
      A21=STHETA*SPHI                                                 4766
      A22=CTHETA                                                      4767
      A23=STHETA*CPHI                                                 4768
      SPHI=PHI                                                        4769
      STHETA=THETA                                                    4770
   80 INCI=-INCI                                                      4771
      IF (I.NE.0) I=NPNTS+1                                           4772
      DO 620 K=1,NPNTS                                                4773
      I=I+INCI                                                        4774
      GO TO (90,100), INDX                                            4775
   90 X=XDATA(1)+(I-1)*XSCALE                                         4776
      GO TO 110                                                       4777
  100 X=XDATA(I)*XSCALE                                               4778
  110 GO TO (120,130), INDY                                           4779
  120 Y=YDATA(1)+(I-1)*YSCALE                                         4780
      GO TO 140                                                       4781
  130 Y=YDATA(I)*YSCALE                                               4782
  140 GO TO (150,160), INDZ                                           4783
  150 Z=ZDATA(1)+(NLINE-1)*ZSCALE                                     4784
      GO TO 170                                                       4785
  160 Z=ZDATA(I)*ZSCALE                                               4786
  170 XXX=A11*X+A13*Z+XREF                                            4787
      XX=XXX                                                          4788
      IF (XX) 180,190,190                                             4789
  180 IX=IFIX(XX*PIPI-0.5)                                            4790
      GO TO 200                                                       4791
  190 IX=IFIX(XX*PIPI+0.5)                                            4792
  200 CONTINUE                                                        4793
      YYY=A21*X+A23*Z+YREF                                            4794
      YY=YYY+A22*Y                                                    4795
      IF (YY) 210,220,220                                             4796
  210 IY=IFIX(YY*PIPI-0.5)                                            4797
      GO TO 230                                                       4798
  220 IY=IFIX(YY*PIPI+0.5)                                            4799
```

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230 CONTINUE                                                          4800
    IF (IX.LE.0) IX=1                                                 4801
    IF (IX.GT.LIMITX) IX=LIMITX                                       4802
    IF (IY.LT.10) IY=10                                               4803
    IF (IY.GT.NYPI) IY=NYPI                                           4804
    IF (K.NE.1) GO TO 310                                             4805
    LOW=IX+IX                                                         4806
    HIGH=LOW-1                                                        4807
    MLOW=MASK(LOW)                                                    4808
    MHIGH=MASK(HIGH)                                                  4809
    IF (MHIGH-IY) 260,270,240                                         4810
240 IF (MLOW-IY) 250,290,280                                          4811
250 LOCOLD=0                                                          4812
    GO TO 300                                                         4813
260 MASK(HIGH)=IY                                                     4814
    IF (MLOW.EQ.-1) MASK(LOW)=IY                                      4815
270 LOCOLD=+1                                                         4816
    GO TO 300                                                         4817
280 MASK(LOW)=IY                                                      4818
290 LOCOLD=-1                                                         4819
300 G1=IX/100.                                                        4820
    G2=IY/100.                                                        4821
    CALL PLOT (G1,G2,3)                                               4822
    JX=IX                                                             4823
    JY=IY                                                             4824
    IYREF=IY                                                          4825
    IF (INDV.EQ.1) GO TO 620                                          4826
    INDEX=INCI+6                                                      4827
    VERTEX(INDEX)=XX                                                  4828
    VERTEX(INDEX+1)=YY                                                4829
    VERTEX(INDEX+8)=XXX                                               4830
    VERTEX(INDEX+9)=YYY                                               4831
    IF (NLINE.NE.1) GO TO 620                                         4832
    VERTEX(1)=XX                                                      4833
    VERTEX(2)=YY                                                      4834
    VERTEX(9)=XXX                                                     4835
    VERTEX(10)=YYY                                                    4836
    GO TO 620                                                         4837
310 IF (IX.NE.JX) GO TO 320                                           4838
    JY=IY                                                             4839
    GO TO 370                                                         4840
320 YINC=FLOAT(IY-JY)/ABS(FLOAT(IX-JX))                               4841
    INCX=(IX-JX)/IABS(IX-JX)                                          4842
    YJ=JY                                                             4843
330 JX=JX+INCX                                                        4844
    YJ=YJ+YINC                                                        4845
    IF (YJ) 340,350,350                                               4846
340 JY=IFIX(YJ-0.5)                                                   4847
    GO TO 360                                                         4848
350 JY=IFIX(YJ+0.5)                                                   4849
360 CONTINUE                                                          4850
    LOW=JX+JX                                                         4851
    HIGH=LOW-1                                                        4852
    MLOW=MASK(LOW)                                                    4853
    MHIGH=MASK(HIGH)                                                  4854
370 IF (MHIGH-JY) 390,390,380                                         4855
380 IF (MLOW-JY) 400,410,410                                          4856
390 LOC=+1                                                            4857
    IF (LOCOLD) 450,460,520                                           4858
400 LOC=0                                                             4859
    IF (LOCOLD) 430,440,420                                           4860
410 LOC=-1                                                            4861
    IF (LOCOLD) 600,540,530                                           4862
420 G1=JX/100.                                                        4863
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      G2=MHIGH/100.                                                    4864
      IF (MHIGH.LE.IYREF) CALL PLOT (G1,G2,2)                          4865
      GO TO 440                                                        4866
  430 G2=MLOW/100.                                                     4867
      IF (MHIGH.GE.IYREF) CALL PLOT (G1,G2,2)                          4868
  440 G1=JX/100.                                                       4869
      G2=JY/100.                                                       4870
      CALL PLOT (G1,G2,3)                                              4871
      GO TO 610                                                        4872
  450 IF (MLOW-IYREF) 460,470,470                                      4873
  460 IF (MHIGH-IYREF) 490,480,480                                     4874
  470 G1=JX/100.                                                       4875
      G2=MLOW/100.                                                     4876
      CALL PLOT (G1,G2,2)                                              4877
  480 G1=JX/100.                                                       4878
      G2=MHIGH/100.                                                    4879
      CALL PLOT (G1,G2,3)                                              4880
      GO TO 520                                                        4881
  490 IF (MHIGH.EQ.-1) GO TO 520                                       4882
      OLDHI=HIGH-2*INCX                                                4883
      IF (MASK(OLDHI)-JY) 510,510,500                                  4884
  500 G1=JX/100.                                                       4885
      G2=JY/100.                                                       4886
      CALL PLOT (G1,G2,3)                                              4887
      GO TO 520                                                        4888
  510 G1=(JX-INCX)/100.                                                4889
      G2=MASK(OLDHI)/100.                                              4890
      CALL PLOT (G1,G2,3)                                              4891
  520 MASK(HIGH)=JY                                                    4892
      IF (MLOW.EQ.-1) MASK(LOW)=JY                                     4893
      G1=JX/100.                                                       4894
      G2=JY/100.                                                       4895
      CALL PLOT (G1,G2,2)                                              4896
      GO TO 610                                                        4897
  530 IF (MHIGH-IYREF) 550,550,540                                     4898
  540 IF (MLOW-IYREF) 560,560,570                                      4899
  550 G1=JX/100.                                                       4900
      G2=MHIGH/100.                                                    4901
      CALL PLOT (G1,G2,2)                                              4902
  560 G1=JX/100.                                                       4903
      G2=MLOW/100.                                                     4904
      CALL PLOT (G1,G2,3)                                              4905
      GO TO 600                                                        4906
  570 OLDLOW=LOW-2*INCX                                                4907
      IF (MASK(OLDLOW)-JY) 580,590,590                                 4908
  580 G1=JX/100.                                                       4909
      G2=JY/100.                                                       4910
      CALL PLOT (G1,G2,3)                                              4911
      GO TO 600                                                        4912
  590 G1=(JX-INCX)/100.                                                4913
      G2=MASK(OLDLOW)/100.                                             4914
      CALL PLOT (G1,G2,3)                                              4915
  600 MASK(LOW)=JY                                                     4916
      G1=JX/100.                                                       4917
      G2=JY/100.                                                       4918
      CALL PLOT (G1,G2,2)                                              4919
  610 IYREF=JY                                                         4920
      LOCOLD=LOC                                                       4921
      IF (JX.NE.IX) GO TO 330                                          4922
  620 CONTINUE                                                         4923
      G1=JX/100.                                                       4924
      G2=JY/100.                                                       4925
      CALL PLOT (G1,G2,3)                                              4926
      IF (INDV.EQ.1) GO TO 630                                         4927
```

```
      INDEX=-INCI+6                                                          4928
      VERTEX(INDEX)=XX                                                       4929
      VERTEX(INDEX+1)=YY                                                     4930
      VERTEX(INDEX+8)=XXX                                                    4931
      VERTEX(INDEX+9)=YYY                                                    4932
      IF (NLINE.NE.1) GO TO 630                                              4933
      VERTEX(3)=XX                                                           4934
      VERTEX(4)=YY                                                           4935
      VERTEX(11)=XXX                                                         4936
      VERTEX(12)=YYY                                                         4937
  630 I=I-1                                                                  4938
      RETURN                                                                 4939
  640 INIT=0                                                                 4940
      RETURN                                                                 4941
      END                                                                    4942
      SUBROUTINE FRAMER (IHCOR,VERTEX,MASK)                                  4943
C                                                                            4944
C                                                                            4945
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4946
C     DRAWS FRAME ABOUT 3-D PLOT                                             4947
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4948
C                                                                            4949
C                                                                            4950
      DIMENSION VERTEX(1), MASK(1), ARRAY(14)                                4951
      I=2*IHCOR                                                              4952
      IF (I.LT.2) I=2                                                        4953
      IF (I.GT.8) I=8                                                        4954
      ARRAY(1)=VERTEX(I-1)                                                   4955
      ARRAY(8)=VERTEX(I)                                                     4956
      ARRAY(2)=VERTEX(I+7)                                                   4957
      ARRAY(9)=VERTEX(I+8)                                                   4958
      ARRAY(4)=ARRAY(2)                                                      4959
      ARRAY(11)=ARRAY(9)                                                     4960
      ARRAY(6)=ARRAY(2)                                                      4961
      ARRAY(13)=ARRAY(9)                                                     4962
      ARRAY(7)=ARRAY(1)                                                      4963
      ARRAY(14)=ARRAY(8)                                                     4964
      I=I-2                                                                  4965
      IF (I.EQ.0) I=8                                                        4966
      ARRAY(3)=VERTEX(I+7)                                                   4967
      ARRAY(10)=VERTEX(I+8)                                                  4968
      I=I+4                                                                  4969
      IF (I.GT.8) I=I-8                                                      4970
      ARRAY(5)=VERTEX(I+7)                                                   4971
      ARRAY(12)=VERTEX(I+8)                                                  4972
      CALL PLOT3D (110,ARRAY,ARRAY(8),0.0,1.0,1.0,0.0,2,7,0.0,0.0,0.0,0.0,0. 4973
     10,0.0,MASK,0)                                                          4974
      CALL PLOT (VERTEX(I-1),VERTEX(I),3)                                    4975
      I=I-2                                                                  4976
      DO 10 J=1,3                                                            4977
      I=I+2                                                                  4978
      IF (I.EQ.10) I=2                                                       4979
      CALL PLOT (VERTEX(I+7),VERTEX(I+8),2)                                  4980
   10 CONTINUE                                                               4981
      CALL PLOT (VERTEX(I-1),VERTEX(I),2)                                    4982
      I=I-2                                                                  4983
      IF (I.EQ.0) I=8                                                        4984
      CALL PLOT (VERTEX(I-1),VERTEX(I),3)                                    4985
      CALL PLOT (VERTEX(I+7),VERTEX(I+8),2)                                  4986
      RETURN                                                                 4987
      END                                                                    4988
      SUBROUTINE PLTMTX (A,NRA,NCA,IVIEW,IOPT,ICROSS,X1,X2,Y1,Y2)            4989
C                                                                            4990
C     THIS IS A 3-D PLOT PACKAGE(2ND) DEVELOPED BY ADTC, EGLIN AFB,FL.       4991
```

```
C                                                                       4992
C                                                                       4993
C     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC  4994
C                                                                       4995
C                                                                       4996
C     THIS IS A GENERAL PURPOSE ROUTINE FOR MAKING AN OBLIQUE PLOT OF   4997
C      A MATRIX OF VALUES.  IT USES PLT3D1 TO ACTUALLY PLOT THE DATA.   4998
C                                                                       4999
C      A = INPUT ARRAY TO BE PLOTTED.                                   5000
C      NRA=NUMBER OF ROWS IN A                                          5001
C     NCA= NUMBER OF COLUMNS IN A                                       5002
C      IVIEW INDICATES VIEWING ANGLE                                    5003
C            = 1, INDICATES VIEW FROM BOTTOM TO TOP                     5004
C            = 2, INDICATES VIEW FROM RIGHT TO LEFT                     5005
C            = 3, INDICATES VIEW FROM TOP TO BOTTOM                     5006
C            = 4, INDICATES VIEW FROM LEFT TO RIGHT                     5007
C      IOPT = 0, INDICATES USE DEFAULT SCALING FOR VERTICAL SCALE        5008
C      IOPT = 1, INDICATES VERTICAL SCALE WILL BE SET BY PROGRAMMER (WTO 5009
C      INTERVAL AT WHICH POINTS BETWEEN CURVES WILL BE CONNECTED (USUALL 5010
C      X1 = VARIABLE ASSIGNED TO LAST ROW                               5011
C     X2=VARIABLE ASSIGNED TO FIRST ROW                                 5012
C     Y1= VARIABLE ASSIGNED TO FIRST COLUMN                             5013
C     Y2= VARIABLE ASSIGNED TO LAST COLUMN                              5014
C                   NOTE- IF DO NOT WISH TO ASSIGN VARIABLES, THEN      5015
C                         SET X1=NRA, X2=1, Y1=1, Y2=NCA.               5016
C                                                                       5017
C     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC  5018
      DIMENSION A(NRA,NCA)                                              5019
      COMMON /MAXVAL/ UFOR,UBACK,VLEFT,VRIGHT,WBOT,WTOP,THETA,UAXIS,VAXI 5020
     1S,UVPLNE,IU(2,2),IV(2,2),IW(2,2),JLAB                             5021
      DIMENSION V(150), W(150)                                          5022
      PRINT 160, NRA,NCA,IVIEW,IOPT,ICROSS,X1,X2,Y1,Y2                  5023
      ZMIN=9999999.                                                     5024
      DX=(X2-X1)/(NRA-1)                                                5025
      DY=(Y2-Y1)/(NCA-1)                                                5026
      JLAB=0                                                            5027
      ZMAX=-999999.                                                     5028
      DO 10 I=1,NRA                                                     5029
      DO 10 J=1,NCA                                                     5030
      ZMAX=AMAX1(ZMAX,A(I,J))                                           5031
      ZMIN=AMIN1(ZMIN,A(I,J))                                           5032
   10 CONTINUE                                                          5033
      IF (IVIEW.GT.4.OR.IVIEW.LT.1) IVIEW=1                             5034
      IF (IOPT.EQ.1) GO TO 20                                           5035
      WTOP=2.*ZMAX                                                      5036
      WBOT=ZMIN                                                         5037
      WBOT=-2.5                                                         5038
      WTOP=12.5                                                         5039
      THETA=.7854                                                       5040
   20 CONTINUE                                                          5041
      UVPLNE=WBOT                                                       5042
      IF (ZMIN.LE.0.AND.ZMAX.GE.0) UVPLNE=0.0                           5043
      CLIPU=99999999.                                                   5044
      CLIPD=-999999999.                                                 5045
      XNOISE=0.0                                                        5046
      GO TO (30,40,50,60), IVIEW                                        5047
   30 UFOR=X2                                                           5048
      UBACK=X1                                                          5049
      DELU=-DX                                                          5050
      DELV=DY                                                           5051
      VLEFT=Y1                                                          5052
      VRIGHT=Y2                                                         5053
      GO TO 70                                                          5054
   40 UFOR=Y2                                                           5055
```

```
      UBACK=Y1                                                          5056
      DELU=-DY                                                          5057
      DELV=-DX                                                          5058
      VLEFT=X2                                                          5059
      VRIGHT=X1                                                         5060
      GO TO 70                                                          5061
   50 UFOR=X1                                                           5062
      UBACK=X2                                                          5063
      DELU=DX                                                           5064
      DELV=-DY                                                          5065
      VLEFT=Y2                                                          5066
      VRIGHT=Y1                                                         5067
      GO TO 70                                                          5068
   60 UFOR=Y1                                                           5069
      DELU=DY                                                           5070
      UBACK=Y2                                                          5071
      DELV=DX                                                           5072
      VLEFT=X1                                                          5073
      VRIGHT=X2                                                         5074
   70 CONTINUE                                                          5075
      UAXIS=VLEFT                                                       5076
      VAXIS=UBACK                                                       5077
      DO 80 I=1,150                                                     5078
   80 W(I)=WBOT                                                         5079
      NCURV=ABS((UFOR-UBACK)/DELU)+2.5                                  5080
      NPTS=ABS((VRIGHT-VLEFT)/DELV)+2.5                                 5081
      DO 150 I=1,NCURV                                                  5082
      U=UFOR+(I-2.)*DELU                                                5083
      IF (I.EQ.1) U=UFOR                                                5084
      DO 140 J=1,NPTS                                                   5085
      V(J)=VLEFT+(J-1.)*DELV                                            5086
      IF (J.EQ.NPTS) V(J)=V(J-1)                                        5087
      IF (I.EQ.1.OR.J.EQ.NPTS) GO TO 140                                5088
      GO TO (90,100,110,120), IVIEW                                     5089
   90 II=NRA-(I-2)                                                      5090
      JJ=J                                                              5091
      GO TO 130                                                         5092
  100 JJ=NCA-(I-2)                                                      5093
      II=NRA-(J-1)                                                      5094
      GO TO 130                                                         5095
  110 II=I-1                                                            5096
      JJ=NCA-(J-1)                                                      5097
      GO TO 130                                                         5098
  120 JJ=I-1                                                            5099
      II=J                                                              5100
  130 CONTINUE                                                          5101
C     PRINT 9004,NCURV,NPTS,I,J,II,JJ ,IVIEW                            5102
      W(J)=A(II,JJ)                                                     5103
      IF (W(J).GT.CLIPU) W(J)=CLIPU                                     5104
      IF (W(J).LT.CLIPD) W(J)=CLIPD                                     5105
      IF (ABS(W(J)).LT.XNOISE) W(J)=XNOISE                              5106
  140 CONTINUE                                                          5107
      IPASS=ICROSS                                                      5108
      IF (I.EQ.1) IPASS=-1                                              5109
      CALL PLT3D1 (U,V,W,IPASS,NPTS)                                    5110
  150 CONTINUE                                                          5111
      DELW=(WTOP-WBOT)/10.                                              5112
      NLV=(NPTS-1)/15+1                                                 5113
      NLU=(NCURV-1)/20+1                                                5114
      CALL PLT3D1 (UBACK,DELW,0.0,-6,1)                                 5115
      CALL PLT3D1 (UBACK,DELU,0.0,-8,NLU)                               5116
      RETURN                                                            5117
C                                                                       5118
  160 FORMAT (1X,5I5,4F10.4)                                            5119
```

```
      END                                                                5120
      SUBROUTINE PLT3D1 (UA,VA,WA,IPASS,NPT)                             5121
C                                                                        5122
C                                                                        5123
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 5124
C     3-D PLOT PACKAGE CONTINUED                                         5125
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 5126
C                                                                        5127
C                                                                        5128
      COMMON /CLASF/ ICLASS,TITLE(7)                                     5129
C                                                                        5130
C     THIS SUBROUTINE WILL MAKE OBLIQUE PLOT OF V VS W FUNCTION FOR      5131
C     A GIVEN U.                                                         5132
C                                                                        5133
C     U= VALUE OF INDEPENDENT VARIABLE U FOR A GIVEN V VS W FUNCTION.    5134
C     VA = ONE DIMENSIONAL ARRAY CONTAINING INDEPENDENT VARIABLE V.      5135
C     WA=ONE DIMENSIONAL ARRAY CONTAINING DEPENDENT VARIABLE W.          5136
C                        WA(I)= F(U,VA(I))                               5137
C     NPTS= NO. OF PTS IN VA, WA ARRAYS.                                 5138
C                                                                        5139
C     NOTE : NPTS=IABS(NPT)                                              5140
C               IF(NPT.LTO) THEN WA(I)=F(UA(I),VA(I))                    5141
C                                                                        5142
C     IPASS=-1 IF THIS IS FIRST CALL FOR NEW FRAME.                      5143
C     IPASS = -6 DRAW LINES FOR W SCALE AND LABEL W SCALE                5144
C               VA(1) IS     DELTA W FOR LABELING                        5145
C               NPTS = LABEL EVERY NPTS LINE                             5146
C     IPASS = -7 DRAW LINES FOR V SCALE AND LABEL V SCALE                5147
C               VA(1) IS     DELTA V FOR LABELING                        5148
C               NPTS = LABEL EVERY NPTS LINE                             5149
C     IPASS = -8 LABEL U SCALE                                           5150
C               VA(1) IS DELTA U FOR LABELING                            5151
C               NPTS = LABEL EVERY NPTS LINE                             5152
C     IPASS = -2 HIDDEN LINES ARE NOT ELIMINATED,                        5153
C               NOT CONNECTED TO PREVIOUS LINE                           5154
C     JLAB IS ALPHA LABEL FOR U SCALE                                    5155
C               JLAB = 0 NOT USED FOR THIS CALL                          5156
C     IPASS=N INDICATES EVERY NTH POINT ON THIS CURVE TO NTH POINT OF    5157
C            PREVIOUS CURVE BE CONNECTED.                                5158
C                                                                        5159
      COMMON /MAXVAL/ UFOR,UBACK,VLEFT,VRIGHT,WBOT,WTOP,THETA,UAXIS,VAXI 5160
     1S,UVPLNE,IU(2,2),IV(2,2),IW(2,2),JLAB                              5161
C                                                                        5162
C     MAXVAL COMMON IS USED FOR DETERMING SCALES.                        5163
C     UFOR=EXTREME VALUE OF U FOR FOREGROUND.                            5164
C     UBACK= EXTREME VALUE OF U FOR BACKGROUND.                          5165
C     VLEFT= LEFT MOST VALUE OF V.                                       5166
C     VRIGHT= RIGHT MOST VALUE OF V                                      5167
C     WBOT=MIN VALUE OF W.                                               5168
C     WTOP=MAX VALUE OF W                                                5169
C     THETA=ANGLE OF OBLIQUE AXIS WITH VERTICAL (RADIANS).  NOTE- IF THI 5170
C     IS ZERO. THEN PLOT WILL BE TWO DIMENSIONAL WITH U AND W AXES CO-   5171
C     INCIDENT.                                                          5172
C     UAXIS= VALUE OF V AT WHICH UAXIS IS TO BE DRAWN.                   5173
C     VAXIS= VALUE OF U AT WHICH V AXIS IS TO BE DRAWN.                  5174
C     UVPLNE= VALUE OF W AT WHICH UAXIS AND VAXIS INTERSECT.             5175
C                                                                        5176
      DIMENSION IXSAV(601), IYSAV(601)                                   5177
      DIMENSION UA(NPT), VA(NPT), WA(NPT)                                5178
      COMMON MINY(1024),MAXY(1024)                                       5179
      LOGICAL IOUT                                                       5180
C                                                                        5181
C                                                                        5182
      NPTS=IABS(NPT)                                                     5183
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```
C     PRINT 8880,UFOR,UBACK,VLEFT,VRIGHT,WBOT,WTOP,IPASS,NPTS                5184
C      PRINT 1000,  U,(VA(JJ),WA(JJ),JJ=1,NPTS)                              5185
      IF (IPASS.GE.0) GO TO 50                                               5186
      IF (IPASS.EQ.-2) GO TO 50                                              5187
      IF (IPASS.LE.-6) GO TO 250                                             5188
C     IF FIRST PASS, ADVANCE FRAME, SET SCALES, AND INITIALIZE MAX AND       5189
C     MIN FUNCTIONS.    THE FIRST CURVE TO BE PLOTTED WILL BE THE FARTHES    5190
C     IN THE FOREGROUND.     SUCCEEDING VALUES OF U MUST BE EITHER           5191
C     ASCENDING OF DESCENDING.                                               5192
C                                                                            5193
      CALL FRAMEV (3)                                                        5194
C     FIND SCALE VALUES TO MAKE VARIABLES PROPORTIONAL                       5195
      ULNTH=ABS(UFOR-UBACK)                                                  5196
      VLNTH=ABS(VRIGHT-VLEFT)                                                5197
      WLNTH=ABS(WTOP-WBOT)                                                   5198
      SCMIN=AMIN1(ULNTH,VLNTH,WLNTH)                                         5199
      SCALU=SCMIN/ULNTH                                                      5200
      SCALV=SCMIN/VLNTH                                                      5201
      SCALW=SCMIN/WLNTH                                                      5202
      SCALU=SCALU*22./69.                                                    5203
      IF (IPASS.NE.-3) GO TO 10                                              5204
      SCALU=1.                                                               5205
      SCALV=1.                                                               5206
      SCALW=1.                                                               5207
   10 CONTINUE                                                               5208
      ULNTH=ULNTH*SCALU                                                      5209
      DIFX=ULNTH*SIN(THETA)                                                  5210
      IF (VRIGHT.LT.VLEFT) DIFX=-DIFX                                        5211
      IF (THETA.GE.0.0) GO TO 20                                             5212
      XRIGHT=VRIGHT*SCALV                                                    5213
      XLEFT=VLEFT*SCALV+DIFX                                                 5214
      GO TO 30                                                               5215
   20 CONTINUE                                                               5216
      XLEFT=VLEFT*SCALV                                                      5217
      XRIGHT=VRIGHT*SCALV+DIFX                                               5218
   30 CONTINUE                                                               5219
      YTOP=(WTOP-WBOT)*SCALW+ULNTH*COS(THETA)+WBOT*SCALW                     5220
      YBOT=WBOT*SCALW                                                        5221
      YSCALE=YTOP-YBOT                                                       5222
      XSCALE=ABS(XRIGHT-XLEFT)                                               5223
      CALL XSCALV (XLEFT,XRIGHT,74,50)                                       5224
      CALL YSCALV (YBOT,YTOP,50,74)                                          5225
      DO 40 I=1,1024                                                         5226
      MINY(I)=1000                                                           5227
      MAXY(I)=0                                                              5228
      IF (I.GT.500) GO TO 40                                                 5229
      IXSAV(I)=0                                                             5230
      IYSAV(I)=0                                                             5231
   40 CONTINUE                                                               5232
C     CONSTRUCT THE AXES.                                                    5233
C                                                                            5234
C     (V AXIS)                                                               5235
      DELU=ABS(VAXIS-UFOR)*SCALU                                             5236
      DX=DELU*SIN(THETA)                                                     5237
      IDELX=(DX/XSCALE)*900.                                                 5238
      DY=DELU*COS(THETA)                                                     5239
      IDELY=(DY/YSCALE)*900.                                                 5240
      IX1=NXV(VLEFT*SCALV)+IDELX                                             5241
      IY1=NYV(UVPLNE*SCALW)+IDELY                                            5242
      IX2=NXV(VRIGHT*SCALV)+IDELX                                            5243
      IY2=IY1                                                                5244
      CALL LINEV (IX1,IY1,IX2,IY2)                                           5245
      IV(1,1)=IX1                                                            5246
      IV(2,1)=IY1                                                            5247
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```
      IV(1,2)=IX2                                                        5248
      IV(2,2)=IY2                                                        5249
C                                                                        5250
C     (W AXIS)                                                           5251
      IX1=NXV(UAXIS*SCALV)+IDELX                                         5252
      IX2=IX1                                                            5253
      IY1=NYV(WBOT*SCALW)+IDELY                                          5254
      IY2=NYV(WTOP*SCALW)+IDELY                                          5255
      CALL LINEV (IX1,IY1,IX2,IY2)                                       5256
      IW(1,1)=IX1                                                        5257
      IW(2,1)=IY1                                                        5258
      IW(1,2)=IX2                                                        5259
      IW(2,2)=IY2                                                        5260
C                                                                        5261
C     (U AXIS)                                                           5262
C                                                                        5263
      IX1=NXV(UAXIS*SCALV)                                               5264
      IY1=NYV(UVPLNE*SCALW)                                              5265
      Y2=ULNTH*COS(THETA)+UVPLNE*SCALW                                   5266
      X2=DIFX+UAXIS*SCALV                                                5267
      IX2=NXV(X2)                                                        5268
      IY2=NYV(Y2)                                                        5269
      CALL LINEV (IX1,IY1,IX2,IY2)                                       5270
      IU(1,1)=IX1                                                        5271
      IU(2,1)=IY1                                                        5272
      IU(1,2)=IX2                                                        5273
      IU(2,2)=IY2                                                        5274
C                                                                        5275
   50 CONTINUE                                                           5276
      U=UA(1)                                                            5277
      IOUT=.TRUE.                                                        5278
      ICOUNT=ICOUNT+1                                                    5279
      J=NPTS+1                                                           5280
      DO 170 JJ=1,NPTS                                                   5281
      IF (THETA) 60,70,70                                                5282
   60 J=JJ                                                               5283
      GO TO 80                                                           5284
   70 J=J-1                                                              5285
   80 CONTINUE                                                           5286
      IF (NPT.LT.0.) U=UA(J)                                             5287
      IF (NPT.GT.0.AND.JJ.GT.1) GO TO 90                                 5288
      DELU=ABS(U-UFOR)*SCALU                                             5289
      DX=DELU*SIN(THETA)                                                 5290
      IDELX=(DX/XSCALE)*900.                                             5291
      DY=DELU*COS(THETA)                                                 5292
      IDELY=(DY/YSCALE)*900.                                             5293
   90 CONTINUE                                                           5294
      IX2=IXV(VA(J)*SCALV)+IDELX                                         5295
      IY2=IYV(WA(J)*SCALW)+IDELY                                         5296
      IF (IPASS.LE.0) GO TO 140                                          5297
      IF (MOD(J-1,IPASS).NE.0) GO TO 140                                 5298
      NX=IABS(IX2-IXSAV(J))                                              5299
      IF (NX.EQ.0) NX=1                                                  5300
      INCX=1                                                             5301
      IF (IXSAV(J).GT.IX2) INCX=-1                                       5302
      DX=NX                                                              5303
      DY=IY2-IYSAV(J)                                                    5304
      RATIO=DY/DX                                                        5305
      IYST=IYSAV(J)                                                      5306
      IX=IXSAV(J)                                                        5307
      IN=0                                                               5308
      DO 130 I=1,NX                                                      5309
      IX=IX+INCX                                                         5310
      IY=IYST+I*RATIO                                                    5311
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```
      IF (IY.LE.MAXY(IX).AND.IY.GE.MINY(IX)) GO TO 100                          5312
      IN=0                                                                      5313
      GO TO 120                                                                 5314
  100 IF (IN.EQ.1.OR.I.EQ.1) GO TO 110                                          5315
      IXCK=IXSAV(J)                                                             5316
      IF (IY.GT.MAXY(IX).AND.IYSAV(J).LT.MAXY(IXCK)) IYSAV(J)=MAXY(IXCK)        5317
      CALL LINEV (IXSAV(J),IYSAV(J),IX,IY)                                      5318
  110 IXSAV(J)=IX                                                               5319
      IYSAV(J)=IY                                                               5320
      IN=1                                                                      5321
  120 CONTINUE                                                                  5322
      MAXY(IX)=MAXO(IY,MAXY(IX))                                                5323
      MINY(IX)=MINO(IY,MINY(IX))                                                5324
  130 CONTINUE                                                                  5325
      IF (IN.EQ.0) CALL LINEV (IXSAV(J),IYSAV(J),IX2,IY2)                       5326
  140 CONTINUE                                                                  5327
      IF (IPASS.NE.-2) GO TO 160                                                5328
      IF (JJ.EQ.1) GO TO 150                                                    5329
      CALL LINEV (IX1,IY1,IX2,IY2)                                              5330
  150 CONTINUE                                                                  5331
      IX1=IX2                                                                   5332
      IY1=IY2                                                                   5333
      IF (JJ.NE.NPTS) GO TO 170                                                 5334
      RETURN                                                                    5335
  160 CONTINUE                                                                  5336
      IXSAV(J)=IX2                                                              5337
      IYSAV(J)=IY2                                                              5338
  170 CONTINUE                                                                  5339
      IX1=IXV(VA(1)*SCALV)+IDELX                                                5340
      IY1=IYV(WA(1)*SCALW)+IDELY                                                5341
      IF (IY1.LT.MAXY(IX1).AND.IY1.GT.MINY(IX1)) IOUT=.FALSE.                   5342
      DO 230 J=2,NPTS                                                           5343
      IX2=IXSAV(J)                                                              5344
      IY2=IYSAV(J)                                                              5345
      NX=IABS(IX2-IX1)                                                          5346
      IF (NX.EQ.0) NX=1                                                         5347
      INCX=1                                                                    5348
      IF (IX2.LT.IX1) INCX=-1                                                   5349
      DX=NX                                                                     5350
      DY=IY2-IY1                                                                5351
      RATIO=DY/DX                                                               5352
      IX=IX1                                                                    5353
      IYST=IY1                                                                  5354
      DO 210 K=1,NX                                                             5355
      IX=IX+INCX                                                                5356
      IY=IYST+K*RATIO                                                           5357
      INDX=IX                                                                   5358
      MXY=MAXY(INDX)                                                            5359
      MNY=MINY(INDX)                                                            5360
      IF (IY.LT.MXY.AND.IY.GT.MNY) GO TO 180                                    5361
      IOUT=.TRUE.                                                               5362
      GO TO 200                                                                 5363
  180 CONTINUE                                                                  5364
      IF (.NOT.IOUT) GO TO 190                                                  5365
      CALL LINEV (IX1,IY1,IX,IY)                                                5366
  190 CONTINUE                                                                  5367
      IOUT=.FALSE.                                                              5368
      IX1=IX                                                                    5369
      IY1=IY                                                                    5370
  200 CONTINUE                                                                  5371
      MAXY(INDX)=MAXO(IY,MXY)                                                   5372
      MINY(INDX)=MINO(IY,MNY)                                                   5373
  210 CONTINUE                                                                  5374
      IF (.NOT.IOUT) GO TO 220                                                  5375
```

```
      CALL LINEV (IX1,IY1,IX2,IY2)                                      5376
  220 CONTINUE                                                          5377
      IND1=IX1                                                          5378
      MAXY(IND1)=MAXO(IY1,MAXY(IND1))                                   5379
      MINY(IND1)=MINO(IY1,MINY(IND1))                                   5380
      IX1=IX2                                                           5381
      IY1=IY2                                                           5382
  230 CONTINUE                                                          5383
      IF (JLAB.EQ.0) GO TO 240                                          5384
C     PRINT HOLERITH JLAB                                               5385
      IXL=IXV(VRIGHT*SCALV)+IDELX+8                                     5386
      IYL=IDELY+IYV(WBOT*SCALW)                                         5387
      CALL PRINTV (8,JLAB,IXL,IYL)                                      5388
      CALL LINE2V (IXL-12,IYL-1.5,0)                                    5389
      CALL LINE2V (IXL-12,IYL-1.5,0)                                    5390
  240 CONTINUE                                                          5391
      RETURN                                                            5392
  250 CONTINUE                                                          5393
      ILAB=0                                                            5394
      IF (IPASS.EQ.-8) GO TO 320                                        5395
      DELU=ABS(UBACK-UFOR)*SCALU                                        5396
      DX=DELU*SIN(THETA)                                                5397
      IDELX=(DX/XSCALE)*900.                                            5398
      DY=DELU*COS(THETA)                                                5399
      IDELY=(DY/YSCALE)*900.                                            5400
      IF (IPASS.EQ.-7) GO TO 280                                        5401
      DELW=VA(1)                                                        5402
      XD=AMAX1(ABS(WTOP),ABS(WBOT))                                     5403
      NDL=NDMAX(XD)                                                     5404
      NDIG=MAXO(5,NDL)                                                  5405
      W=WBOT                                                            5406
      IX1=NXV(VLEFT*SCALV)+IDELX                                        5407
      IX2=NXV(VRIGHT*SCALV)+IDELX                                       5408
  260 IY1=NYV(W*SCALW)+IDELY                                            5409
      IY2=IY1                                                           5410
      CALL LINEV (IX1,IY1,IX2,IY2)                                      5411
      IF (MOD(ILAB,NPTS).NE.0) GO TO 270                                5412
      CALL LABLV (W,IX1-52,IY1,NDIG,1,NDL)                              5413
      CALL LABLV (W,IX1-52,IY1,NDIG,1,NDL)                              5414
  270 CONTINUE                                                          5415
      ILAB=ILAB+1                                                       5416
      W=W+DELW                                                          5417
      IF (W.GT.WTOP) GO TO 240                                          5418
      GO TO 260                                                         5419
  280 CONTINUE                                                          5420
      DELV=VA(1)                                                        5421
      V=VLEFT                                                           5422
      VR=VRIGHT+.01*(VRIGHT-VLEFT)                                      5423
  290 IX1=NXV(V*SCALV)+IDELX                                            5424
      IY2=NYV(WTOP*SCALW)+IDELY                                         5425
      IY1=NYV(WBOT*SCALW)+IDELY                                         5426
      IX2=IX1                                                           5427
      IX3=IX1-IDELX                                                     5428
      IY3=IY1-IDELY                                                     5429
      CALL LINEV (IX1,IY1,IX2,IY2)                                      5430
      IF (MOD(ILAB,NPTS).NE.0) GO TO 300                                5431
      CALL LABLV (V,IX2-28,IY2+6,NDIG,1,NDL)                            5432
      CALL LABLV (V,IX2-28,IY2+6,NDIG,1,NDL)                            5433
      CALL LABLV (V,IX3-28,IY3-6,NDIG,1,NDL)                            5434
      CALL LABLV (V,IX3-28,IY3-6,NDIG,1,NDL)                            5435
  300 CONTINUE                                                          5436
      ILAB=ILAB+1                                                       5437
      V=V+DELV                                                          5438
      IF (VRIGHT.GT.VLEFT) GO TO 310                                    5439
```

```
      IF (V.LT.VR) GO TO 240                                              5440
      GO TO 290                                                           5441
  310 IF (V.GT.VR) GO TO 240                                              5442
      GO TO 290                                                           5443
  320 CONTINUE                                                            5444
      UB=UBACK+.01*(UBACK-UFOR)                                           5445
      ULAB=UFOR                                                           5446
  330 CONTINUE                                                            5447
      DELAB=ABS(ULAB-UFOR)*SCALU                                          5448
      DX=DELAB*SIN(THETA)                                                 5449
      DY=DELAB*COS(THETA)                                                 5450
      IDELX=(DX/XSCALE)*900.                                              5451
      IDELY=(DY/YSCALE)*900.                                              5452
      IX1=NXV(VLEFT*SCALV)+IDELX                                          5453
      IX2=NXV(VRIGHT*SCALV)+IDELX                                         5454
      IY1=NYV(WBOT*SCALW)+IDELY                                           5455
C     CALL POINTV(IX1,IY1,6,ANY)                                          5456
C     CALL POINTV(IX2,IY1,6,ANY)                                          5457
      IF (MOD(ILAB,NPTS).NE.0) GO TO 340                                  5458
C     CALL LABLV(ULAB,IX1-45,IY1.5,1.4)                                   5459
C     CALL LABLV(ULAB,IX1-45,IY1.5,1.4)                                   5460
      ICH=4                                                               5461
      IF (ABS(ULAB).GT.9.) ICH=5                                          5462
      IF (ABS(ULAB).GT.99.) ICH=6                                         5463
      CALL LABLV (ULAB,IX2+4,IY1.ICH.1.ICH-2)                             5464
      CALL LABLV (ULAB,IX2+4,IY1.ICH.1.ICH-2)                             5465
  340 ILAB=ILAB+1                                                         5466
      ULAB=ULAB+VA(1)                                                     5467
      IF (UBACK.LT.UFOR) GO TO 350                                        5468
      IF (ULAB.GT.UB) GO TO 240                                           5469
      GO TO 330                                                           5470
  350 IF (ULAB.LT.UB) GO TO 240                                           5471
      GO TO 330                                                           5472
C                                                                         5473
      END                                                                 5474
      FUNCTION NDMAX(X)                                                   5475
C                                                                         5476
C                                                                         5477
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 5478
C     THIS FUNCTION RETURNS THE MAXIMUM DECIMAL SCALE NEEDED              5479
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 5480
C                                                                         5481
C                                                                         5482
C      FOR USE WITH LABLV                                                 5483
      AX=ABS(X)*10.+.01                                                   5484
      DIG=ALOG10(AX)                                                      5485
      NDMAX=DIG                                                           5486
      IF (DIG.LT.0) NDMAX=0                                               5487
      IF (NDMAX.GT.6) NDMAX=6                                             5488
      RETURN                                                              5489
      END                                                                 5490
      SUBROUTINE FRAMEV (IARG)                                            5491
      DATA IK/0/                                                          5492
      IK=IK+1                                                             5493
      IF (IK.EQ.1) CALL GSIZE (200.,11.,1100)                             5494
      IF (IK.EQ.1) CALL PLOT (0.,0.5,-3)                                  5495
      IF (IK.GT.1) CALL PLOT (10.,0.0,-3)                                 5496
      WRITE (6,10)                                                        5497
      RETURN                                                              5498
C                                                                         5499
10    FORMAT(10X,15H FRAMEV CALLED     )                                  5500
      END                                                                 5501
      SUBROUTINE LINEV (I1,I2,I3,I4)                                      5502
      DATA MI3,MI4/0,0/                                                   5503
```

```
      IP=0                                                                5504
      IF (I1.EQ.MI3.AND.I2.EQ.MI4) IP=1                                   5505
      X1=I1/102.3                                                         5506
      X2=I3/102.3                                                         5507
      Y1=I2/102.3                                                         5508
      Y2=I4/102.3                                                         5509
      IF (IP.EQ.0) CALL PLOT (X1,Y1,+3)                                   5510
      CALL PLOT (X2,Y2,+2)                                                5511
      MI3=I3                                                              5512
      MI4=I4                                                              5513
      RETURN                                                              5514
      END                                                                 5515
      SUBROUTINE PLOT (A,B,IPL)                                           5516
      COMMON /X1/ IZ                                                      5517
      IZ=16                                                               5518
      IF (IPL.EQ.999) CALL CLASS (4,3,0,0)                                5519
      IF (IPL.EQ.999) CALL CALCMP (0.,0.,9999,2)                          5520
      IF (IPL.EQ.-3) CALL CALCMP (0.,0.,0000,2)                           5521
      IF (IPL.EQ.2) CALL CALCMP (A,B,IZ,1)                                5522
      IF (IPL.EQ.3) CALL CALCMP (A,B,0,1)                                 5523
      RETURN                                                              5524
      END                                                                 5525
      SUBROUTINE GSIZE (AA1,AA2,IXX)                                      5526
      LDEV=8                                                              5527
      CALL CALCMP (0.,2.,LDEV,0)                                          5528
      CALL CLASS (1,3,0,0)                                                5529
      RETURN                                                              5530
      END                                                                 5531
      SUBROUTINE DXDYV(I1,ALEFT,ARIGHT,DX,I2,I3,I4,I5,I6)                 5532
      DX=(ARIGHT-ALEFT)/10.                                               5533
      RETURN                                                              5534
      END                                                                 5535
      SUBROUTINE PLOTV(I1,I2,I3)                                          5536
      RETURN                                                              5537
      END                                                                 5538
      SUBROUTINE PRINTV(I1,A,I2,I3)                                       5539
      RETURN                                                              5540
      END                                                                 5541
      SUBROUTINE CHSIZV(I1,I2)                                            5542
      RETURN                                                              5543
      END                                                                 5544
      SUBROUTINE RITE2V(I1,I2,I3,I4,I5,I6,I7,A,I9)                        5545
      RETURN                                                              5546
      END                                                                 5547
      SUBROUTINE XSCALV(A,B,I1,I2)                                        5548
      RETURN                                                              5549
      END                                                                 5550
      SUBROUTINE YSCALV(A,B,I1,I2)                                        5551
      RETURN                                                              5552
      END                                                                 5553
      SUBROUTINE LABLV(A,I1,I2,I3,I4,I5)                                  5554
      RETURN                                                              5555
      END                                                                 5556
      SUBROUTINE LINE2V(I1,I2,I3,I4)                                      5557
      RETURN                                                              5558
      END                                                                 5559
      FUNCTION IXV(A)                                                     5560
      IXV=0                                                               5561
      RETURN                                                              5562
      END                                                                 5563
      FUNCTION IYV(A)                                                     5564
      IYV=0                                                               5565
      RETURN                                                              5566
      END                                                                 5567
```

```
      FUNCTION NXV(A)                                                    5568
      NXV=0                                                              5569
      RETURN                                                             5570
      END                                                                5571
      FUNCTION NYV(A)                                                    5572
      NYV=0                                                              5573
      RETURN                                                             5574
      END                                                                5575
C/          SRR00894,03,G61K),09999FELDMAN,MSGLEVEL=1,                   5576
C/    CLASS=D,REGION=512K,TIME=10                                        5577
C/    EXEC FTGINCGO,PGMNO=SRR00894,OVERLAY=OVLY                          5578
C/SYSIN DD *                                                             5579
C*                                                                       5580
C/LNK.SYSLIN DD *                                                        5581
CINCLUDE SYSTFORT                                                        5582
CINCLUDE FORTEPDS(SRR00894)                                              5583
 OVERLAY TWO                                                             5584
 INSERT DRIVER,INPUT,GEOM,BOUND,OBLQUE,PLATE,SPEC,HULLP1,HULLP2          5585
 INSERT TMESTP,CURRNT,OUTPUT,GRAPH,DIGPLT,PRTPLT,EFIELD,BNDPOT,CUR,DFSN  5586
 INSERT TEMDIF,VIS,TRID,KSWEEP,JSWEEP,GAMM,SIG,BETA,CP,RGAS,COND,CV      5587
 INSERT EDDY,B                                                           5588
 INSERT CARRAY,GRAVTY,CTIME,CMATRX,CSTORE,CSTRSS,CMAGN,ETRODE            5589
 OVERLAY TWO                                                             5590
 INSERT PLOTTE,RDPLT,LABPLT,NXVOSB,LEVEL,POINT,DRAW,TRUN,ARROW,PARTCL    5591
 INSERT CELL,PLOT3D,FRAMER,GRIDS,SHADE,THREED,PLTMTX,PLT3D1,NDMAX        5592
 INSERT P1,P2,P3,P4                                                      5593
 ENTRY MAIN                                                              5594
C*                                                                       5595
C/GO.FT08F001 DD UNIT=2400,DISP=(,KEEP),DSN=WPL1,DCB=DEN=2,LABEL=(,BLP)  5596
C/GO.FT14F001 DD UNIT=WORK,SPACE=(CYL,(5,5),RLSE,,ROUND),                5597
C/    DCB=RECFM=VBS                                                      5598
C/GO.FT05F001 DD *                                                       5599
EOF                                                                      5600
```

NOMENCLATURE

Symbol	Description
A	Elliptic equation coefficient/finite difference coefficient
A	Prandtl Mixing Length coefficient
A	Area
B	Elliptic equation coefficient/finite difference coefficient
$\bar{B}$	Magnetic induction vector
B_r	Radial magnetic induction
B_x	Axial magnetic induction
B_θ	Aximuthal magnetic induction
C	Elliptic equation coefficient/finite difference coefficient
C_s	Shock velocity
c	Speed of sound/electrode thickness
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
D	Finite difference coefficient
$\bar{E}$	Electric field vector
e	Total energy per unit mass
F	Scalar quantity representing ϕ or ψ
F_m	Mass flux
$\bar{g}$	Gravitational acceleration vector
g_z	Axial gravitational acceleration
g_r	Radial gravitational acceleration
h	Channel width
H_a	Hartmann number

Symbol	Description
I	Current
i	Internal energy per unit mass
$\bar{j}$	Current vector
j_r	Radial current
j_z	Axial current
K	Load factor
L	Differential operator
M	Mass
M	Mach number
M_r	Radial magnetic flux
M_z	Axial magnetic flux
M_θ	Aximuthal magnetic flux
$\hat{n}$	Unit vector normal to surface
P	Dimensionless pressure
p	Pressure
$\bar{q}$	Heat flux vector
r	Radial coordinate
Re	Reynolds number
Re_m	Magnetic Reynolds number
S	Electrode + Insulator thickness
t	Time
T	Temperature
U	Particle velocity
u	Scalar velocity in axial direction
$\bar{v}$	Velocity vector
v	Scalar velocity in radial direction

Symbol	Description
x	Cartesian coordinate
y	Cartesian coordinate
z	Axial or Cartesian coordinate
α	Coordinate system; Cartesian = (0); axisymmetric = (1)
β	Hall parameter
δ	Boundary layer thickness
γ	Specific heat ratio
ε	Integration parameter; explicit = (0); implicit = (1)
ε	Strain element
λ_E^2	Prandtl mixing length
λ	Thermal conductivity
λ_t	Thermal conductivity (turbulent)
$\overline{\overline{\sigma}}$	Electrical conductivity tensor
ρ	Density
σ	Scalar conductivity
σ_+	Scalar conductivity corrected for Hall current
ϕ	Electrical potential
ψ	Current stream function
$\overline{\overline{\tau}}$	Viscous and/or magneto stress tensor
τ	Stress element
θ	Aximuthal coordinate
μ	Laminar viscosity
μ_E	Eddy viscosity
μ_p	Magnetic permeability
ω	Relaxation Parameter

Symbol	Description
Superscripts	
n	Time cycle
$\vec{\ }$	Vector
$\overline{\ }$	Tensor
Subscripts	
i	Radial index
j	Axial index
$\vert_s$	Isentropic
rr	r face, r direction
w	wall
zz	z face, z direction
$\theta\theta$	θ face, θ direction
rz	r face, z direction
∞	Infinity
Mathematical Operators	
$\frac{\partial}{\partial t}$	Partial derivative
$\frac{d}{dt}$	Total derivative
∇	"Del" operator
$\cdot$	Vector "dot" product
x	Vector "cross" product
Δ	Finite change